

Article

Modelling the Permeabilities of Dry Filament Wound Cylindrical Reinforcements for RTM Simulation

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Abstract: The production rate of filament wound composites can be improved by using the resin transfer moulding (RTM) process on dry filament wound reinforcements. Finite-element simulation of the resin flow in the porous dry fibre preform is needed to understand and improve the RTM process and to lower development time and cost. However, in a filament wound preform, the fibre volume content and the stacking sequence related to winding angles vary with geometry. This paper presents a new and simple modelling approach which quickly predicts the local principal directions and values of the permeabilities of a dry filament wound preform. In dry filament winding, dry unidirectional fibres are wound on a mandrel so that each element in the RTM simulation contains a multidirectional stacking. Thus, the model uses experimental permeabilities of a unidirectional stacking to predict the permeabilities of a multidirectional stacking for each element. Comparisons between calculated and experimental permeabilities of flat multidirectional stackings show a nesting effect on the permeabilities of the unidirectional stacking used as model input. A calculation method to recalibrate the input permeabilities of the dry unidirectional tape, based on measurements with minimal nesting, is offered. Better predictions are then obtained. The absolute percentage changes with experimental values were limited to 63.9% and 103.6% on in-plane and out-of-plane permeabilities, which had an order of magnitude of 1×10^{-12} and 1×10^{-13} , respectively.



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Keywords: composites; dry filament winding; RTM process; permeabilities modelling; finite-element simulation

1. Introduction

Composite parts made by filament winding are today mainly based on impregnated fibre bundles. The bundles are made of prepregs or are impregnated by using a resin bath, and curing is performed in an autoclave which limits the production rate as compared to the RTM process. In the dry filament winding process, dry fibre bundles are wound on a mandrel. The resulting dry filament wound preforms are then impregnated using the RTM process [1], which enhances the production rate of filament wound composites. The preform is a dry multidirectional structural reinforcement with typically a cylindrical shape. It can be compact and of significant thicknesses, up to several centimetres for example. This constitutes a challenge for the impregnation of the dry preform by the RTM process. Finite-element simulation of the RTM process is therefore necessary to understand and improve the resin flow in the porous dry preform during the filling step, avoid dry areas and minimize voids, and lower development time and costs.

Most of the filament winding process simulation techniques bear upon prepreg or wet filament winding [1]. The simulations provide the trajectories of the impregnated fibre

tape, pattern generation, and aim at providing a reliable model for subsequent filling simulation from impregnated tape and structural simulation. For example, the thermochemical model, fibre consolidation model, and resin bleeding/mixing model are mentioned in the literature [1]. When it comes to dry filament winding, some modelling techniques also bear upon dry fibre path calculation, and the advantages and challenges of subsequent RTM impregnation have already been highlighted to some extent [2]. However, RTM simulation of dry filament-wound preform appears to be challenging and uncommon.

Indeed, in RTM simulation, the permeability of the fibre preform is a very important parameter. In dry filament winding, the dry unidirectional (UD) tape is wound on a mandrel with different winding angles so that in the dry preform, the fibre volume fraction (FVC) and the stacking sequence vary locally with the part geometry. The inputs of the simulation workflow include a two-dimensional (2D) axisymmetric model of the preform made with the filament winding modelling software. The preform resulting from different winding patterns, such as sequences of hoop and helical or polar layers, is modelled precisely. The 2D axisymmetric model contains a 2D mesh which is discretized in local sections. Each section is made of a group of adjacent elements which are assumed to have the same properties at the section level. Since a unidirectional (UD) tape is wound around a mandrel in the dry filament winding process, each finite-element section is made of a multidirectional stack of plies. There can be a high number of sections, up to thousands, for example. Performing thousands of permeability experimental measurements can be costly, time-consuming, and would be useful for only one dry preform. If the filament winding angles are changed, the experimental measurement would have to be performed again for the new preform. It is therefore needed to develop a simple and flexible modelling approach which quickly predicts the principal permeabilities of different multidirectional stackings and reduces time and development costs.

Previous work on the permeability of UD reinforcement for RTM has been performed [3]. The general approach is to adopt Darcy's law to describe the impregnation of the fluid into the porous fibre network created by the dry fibre preform. Analytical expressions of the permeability variation with fibre volume fraction were given along the fibre and perpendicular to the fibre, depending on the arrangement of the fibres. When the UD reinforcement is orientated, the permeability values and directions of the UD ply in the local coordinate system, which are also known as the principal values and directions of permeability, are the eigenvalues and eigenvectors of the permeability tensor [4]. Thus, it is possible to obtain the permeability tensor in the local coordinate system by diagonalizing the permeability tensor of the UD ply in the global coordinate system. Inversely, it is necessary to operate a system change, corresponding to a rotational transformation of the permeability tensor in the local coordinate system, to obtain the permeability tensor in the global coordinate system.

Other works have shown that the permeabilities of a multidirectional stacking in the global coordinate system can be obtained by homogenizing the permeabilities of the oriented UD plies it is made of [5,6]. The homogenization method relies on the calculation of average permeabilities. The reinforcement could typically be considered homogenous with an average permeability, considering the superposition of unidirectional flows in each layer. It was shown that the average permeability of a multi-layer reinforcement can then be defined with a harmonic average in series (out-of-plane flow) and an arithmetic average in parallel (in-plane flow) [7]. The permeability tensor is then averaged in the global coordinate system of the stacking. Finally, the permeability tensor of the multidirectional stacking, averaged in the global coordinate system, can be diagonalized to obtain the principal permeability values and directions of the stacking. It was put forward that this can be performed for a porous medium such as fibre reinforcements [8,9]. Experimentally,

the in-plane principal directions of a dry preform correspond to the major and minor axes of the ellipse formed by the resin impregnating the dry preform [4].

It may be important to highlight here that there can be various side effects when considering the flow in the fibrous preform. It has been shown that a coupled flow model, which considers microflow in a bundle and microflow around bundles simultaneously, predicts enhanced results [7]. More generally, size effects and architectural heterogeneities can be expected to impact permeabilities [10]. Various works have studied the in-plane permeabilities of advanced textiles such as fabrics and triaxial braids and fabrics [11,12]. The corresponding modelling approaches are typically based on the textile unit cell modelling of the textile and do not address the issue of dry filament wound preforms, which do not contain a unit cell. There can also be an interaction between the effects of flows in different directions, like in a multidirectional preform. It was put forward that the flow is mainly located in the layer and directions with the highest permeabilities [13]. Thus, the difference in permeability between layers may lead to different flow front velocities in each layer. However, it was also put forward that the non-uniformity of the flow can be neglected in most cases [14]. Another important effect on the permeability of fibre preforms is the “nesting” effect, which corresponds to the interpenetration between layers, leading to a more compact arrangement. Comparisons were made between theoretical permeabilities with experimental permeabilities of reinforcement stackings made of the same reinforcement but with different lay-up sequences [15]. A “nesting” effect between the layers of the permeabilities was put forward, which depends on the stacking sequence. Other work studied or highlighted the nesting effect in layered preforms [16–21]. Nesting is expected to be more pronounced in unidirectional fabrics, which ease layer interpenetrations.

If the state of the art provides some permeability sub-models, there is a lack of a modelling approach for the permeabilities of dry filament wound fibre reinforcements. Thus, the objective of this paper is to present a new modelling approach to calculate and quickly predict the local principal permeabilities, values, and directions in dry filament wound preforms. Since filament winding consists of winding dry UD fibres around a mandrel, this modelling approach is based on the experimental principal permeabilities of a dry UD stack. The new modelling approach links existing sub-models to calculate the principal permeabilities locally, for each multidirectional stacking contained in each element of the RTM finite-element simulation. For a cylindrical filament wound dry preform, a 2D axisymmetric mesh is rotated to obtain a 3D mesh of the cylinder. Coordinate system changes and rotational transformations on the principal directions are made depending on the position of each 3D element on the cylinder. Comparisons are made with existing results from the literature and with experimental measurements to evaluate the accuracy of this permeability modelling approach. It shows a nesting effect on the UD permeability inputs used in the model. A method to recalibrate the permeability of the UD fibre tape is offered. Improved predictions are then obtained with quite simple and fast calculations.

2. Theory

In this section, the homogenization method of a multidirectional stacking is described. It is applied at the element level, that is, locally, because in a filament wound model, each element is made of a multidirectional stacking. The reason is that the level of discretization is higher than the thickness of the UD fibre tape.

2.1. General Sketch

It is assumed that a cylindrical filament-wound dry preform is made of the same fibre material, such as a high-strength carbon fibre. The global and local coordinate systems are defined and described in Figure 1.

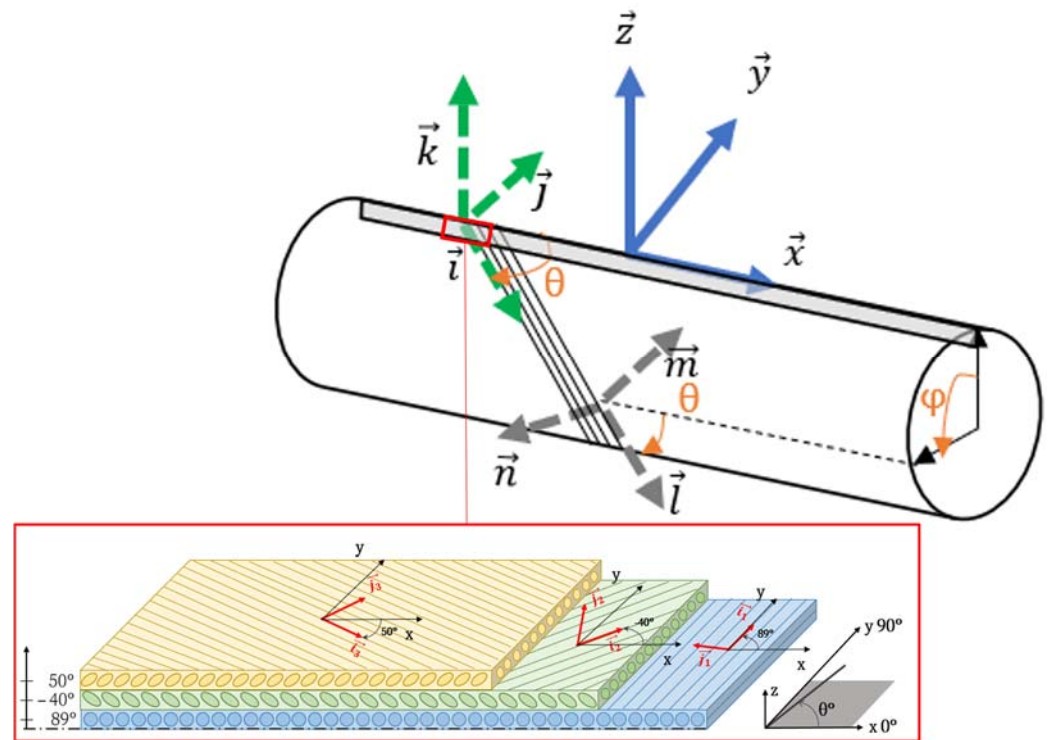


Figure 1. Coordinate systems and rotation angles for a filament wound model. Drawing at the scale of the tube (macroscopic) and the scale of a local stacking (mesoscopic).

Three coordinate systems are defined.

- $(\vec{x}, \vec{y}, \vec{z})$ corresponds to the “global” coordinate system or “geometric” coordinate system of the multidirectional stacking of a 2D-axisymmetric element;
- $(\vec{l}_n, \vec{j}_n, \vec{k}_n)$ corresponds to the principal directions of a unidirectional ply of a 2D-axisymmetric element;
- $(\vec{l}, \vec{j}, \vec{k})$ corresponds to the principal directions of the multidirectional stacking of a 2D-axisymmetric element;
- θ is the “principal” angle between the principal directions $(\vec{l}, \vec{j})$ of the multidirectional stacking of a 2D-axisymmetric element and the stacking global coordinate system $(\vec{x}, \vec{y})$. φ is the “revolution angle”, which depends on the position of the 3D element. $(\vec{l}, \vec{m}, \vec{n})$ correspond to the principal directions of the multidirectional stacking of the 3D element. The following sections describe the steps of the method used to calculate the principal permeabilities (the values and the directions $(\vec{l}, \vec{m}, \vec{n})$) of each 3D element of the dry preform.

2.2. Calculation of the Principal Permeability Tensor of a UD Ply as a Function of the Fibre Volume Fraction and Based on Experimental Measurements

The 3D Darcy’s law which governs the filling of the UD ply number n contained in the multidirectional stacking of a 2D axisymmetric element is given by Equations (1) and (2), [4].

$$\begin{pmatrix} V_{i_n} \\ V_{j_n} \\ V_{k_n} \end{pmatrix} = -\frac{1}{\eta} \bar{\bar{K}}_{ply(\vec{l}_n, \vec{j}_n, \vec{k}_n)} \begin{pmatrix} \partial P / \partial i_n \\ \partial P / \partial j_n \\ \partial P / \partial k_n \end{pmatrix} \quad (1)$$

where P is the pressure field in the resin, V is the flow velocity field, and η is the viscosity of the resin assumed to be Newtonian (Pa·s). $\bar{\bar{K}}_{ply(\vec{l}_n, \vec{j}_n, \vec{k}_n)}$ is the permeability tensor

of the UD ply in the principal coordinate system of the ply. The principal coordinate system $(\vec{l}_n, \vec{j}_n, \vec{k}_n)$ corresponds to the eigenvectors of the permeability tensor, which are the principal flow directions of a UD ply. Thus, $\bar{\bar{K}}_{ply(\vec{l}_n, \vec{j}_n, \vec{k}_n)}$ is given by Equation (2), [4].

$$\bar{\bar{K}}_{ply(\vec{l}_n, \vec{j}_n, \vec{k}_n)} = \begin{bmatrix} K_{i_n} & 0 & 0 \\ 0 & K_{j_n} & 0 \\ 0 & 0 & K_{k_n} \end{bmatrix}_{(\vec{l}_n, \vec{j}_n, \vec{k}_n)} \quad (2)$$

where FVC is the fibre volume content (in %), $K_{i_n}(FVC)$ and $K_{j_n}(FVC)$ are the principal in-plane permeabilities, and $K_{k_n}(FVC)$ is the out-of-plane permeability.

2.3. Calculation of the Permeability Tensor of an Orientated UD Ply (Winding Angle) in the Global Coordinate System

In the global coordinate system $(\vec{x}, \vec{y}, \vec{z})$, the 3D Darcy's law of the UD ply number n contained in the multidirectional stacking of a 2D axisymmetric element is given by Equation (3), [4].

$$\begin{pmatrix} V_{n_x} \\ V_{n_y} \\ V_{n_z} \end{pmatrix} = -\frac{1}{\eta} \bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})} \begin{pmatrix} \partial P_n / \partial x \\ \partial P_n / \partial y \\ \partial P_n / \partial z \end{pmatrix} \quad (3)$$

where $\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})}$ is the permeability tensor of the UD ply in the global coordinate system of the multidirectional stacking to which the ply belongs and is given by Equation (4), [4].

$$\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{xy} & K_{yy} & K_{yz} \\ K_{xz} & K_{yz} & K_{zz} \end{bmatrix}_{(\vec{x}, \vec{y}, \vec{z})} \quad (4)$$

where K_{pq} is the permeability of the reinforcement in the p -direction for a flow in the q -direction (m^2). The components of $\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})}$ depends on the winding angle θ_n of the ply. The permeability tensor $\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})}$ is a symmetrical tensor and is calculated by the mean of a rotation P_{θ_n} of the angle θ_n with respect to the out-of-plane axis according to Equations (5)–(7), [4].

$$\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})} = P_{\theta_n} \bar{\bar{K}}_{ply(\vec{l}, \vec{j}, \vec{k})} P_{\theta_n}^{-1} \quad (5)$$

$$P_{\theta_n} = \begin{bmatrix} \cos \theta_n & \sin \theta_n & 0 \\ -\sin \theta_n & \cos \theta_n & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})} = \begin{bmatrix} K_{i_n} \cos^2 \theta_n + K_{j_n} \sin^2 \theta_n & (K_{i_n} - K_{j_n}) \cos \theta_n \sin \theta_n & 0 \\ (K_{i_n} - K_{j_n}) \cos \theta_n \sin \theta_n & K_{j_n} \cos^2 \theta_n + K_{i_n} \sin^2 \theta_n & 0 \\ 0 & 0 & K_{k_n} \end{bmatrix} \quad (7)$$

2.4. Homogenization of the Permeability Tensor of a Multidirectional Stacking in the Stacking Global Coordinate System

$\bar{\bar{K}}_{\theta_n ply(\vec{x}, \vec{y}, \vec{z})}$ is calculated for each of the n plies of the multidirectional stacking of a 2D-axisymmetric element. An arithmetic average is applied to the permeability values to obtain the equivalent in-plane permeabilities of the whole multidirectional stacking $\bar{\bar{K}}_{eq, in-plane}$ according to Equation (8), [5–7].

$$K_{eq, (\vec{x}, \vec{y})} = \frac{\sum_{i=1}^n K_i h_i}{\sum_{i=1}^n h_i} \quad (8)$$

where h_i is the thickness of ply number i , and K_i are the permeability values of ply number i in the x and y directions. For the out-of-plane permeabilities, the values for each ply are the same. But if this was not the case, a harmonic average would be applied to obtain the homogeneous out-of-plane permeability $K_{eq, \vec{z}}$ of the entire lay-up as shown in Equation (9), [5–7].

$$\frac{\sum_{i=1}^n h_i}{K_{eq, \vec{z}}} = \sum_{i=1}^n \frac{h_i}{K_i} \quad (9)$$

where h_i is the thickness of ply number i , and K_i are the permeability values of ply number i in the z direction.

2.5. Calculation of the Principal Permeabilities of the Multidirectional Stacking of Each 2D-Axisymmetric Section

This homogenization method leads to a non-diagonal matrix. The principal permeabilities correspond to the eigenvalues and eigenvectors of the permeability matrix. Thus, a diagonalization operation of the homogenized permeability tensor of the stacking is performed to obtain the principal permeabilities of the stacking (values and directions). In our case, the homogenized permeability tensor of the multidirectional stacking is always symmetric and is made of real numbers. It can therefore be diagonalized as described in Equation (10), [8,9].

$$\overline{\overline{K}}_{stacking(\vec{l}, \vec{j}, \vec{k})} = \begin{bmatrix} K_i & 0 & 0 \\ 0 & K_j & 0 \\ 0 & 0 & K_k \end{bmatrix}_{(\vec{l}, \vec{j}, \vec{k})} \quad (10)$$

2.6. Rotational Transformations of the Geometric Global Coordinate System for Each Element

Filament winding allows the manufacturing of 3D revolution parts. The input here is the 3D mesh of the cylindrical dry preform. It is possible to define the principal direction of each 3D element $(\vec{l}, \vec{m}, \vec{n})$ by two rotations, already shown in Figure 1 of the geometrical directions $(\vec{x}, \vec{y}, \vec{z})$ of the 2D axisymmetric model:

- Rotation around $\vec{x}$ by φ : one rotation around the revolution axis of the part. The “revolution angle” φ depends on the position of the 3D element and is calculated by means of a scalar product using the position of each 3D tetra element (barycenter) and the position of the section of the 2D axisymmetric model from which it has been generated by spinning the model;
- Rotation around $\vec{n}$ by θ : the “stacking principal angle” θ between the principal directions of the stacking $(\vec{l}, \vec{j})$ and the stacking global coordinate system $(\vec{x}, \vec{y})$ is calculated by means of a scalar product between these two coordinate systems.

3. Materials and Methods

3.1. General Workflow

The homogenization method was implemented using Python 3.9.7. The input is an .inp file of the 2D axisymmetric model made by a filament winding software. The output is an .Iperm file containing the principal permeabilities (values and directions) for each 3D element. The Python modelling strategy is shown in Figure 2 and described in the next sections.

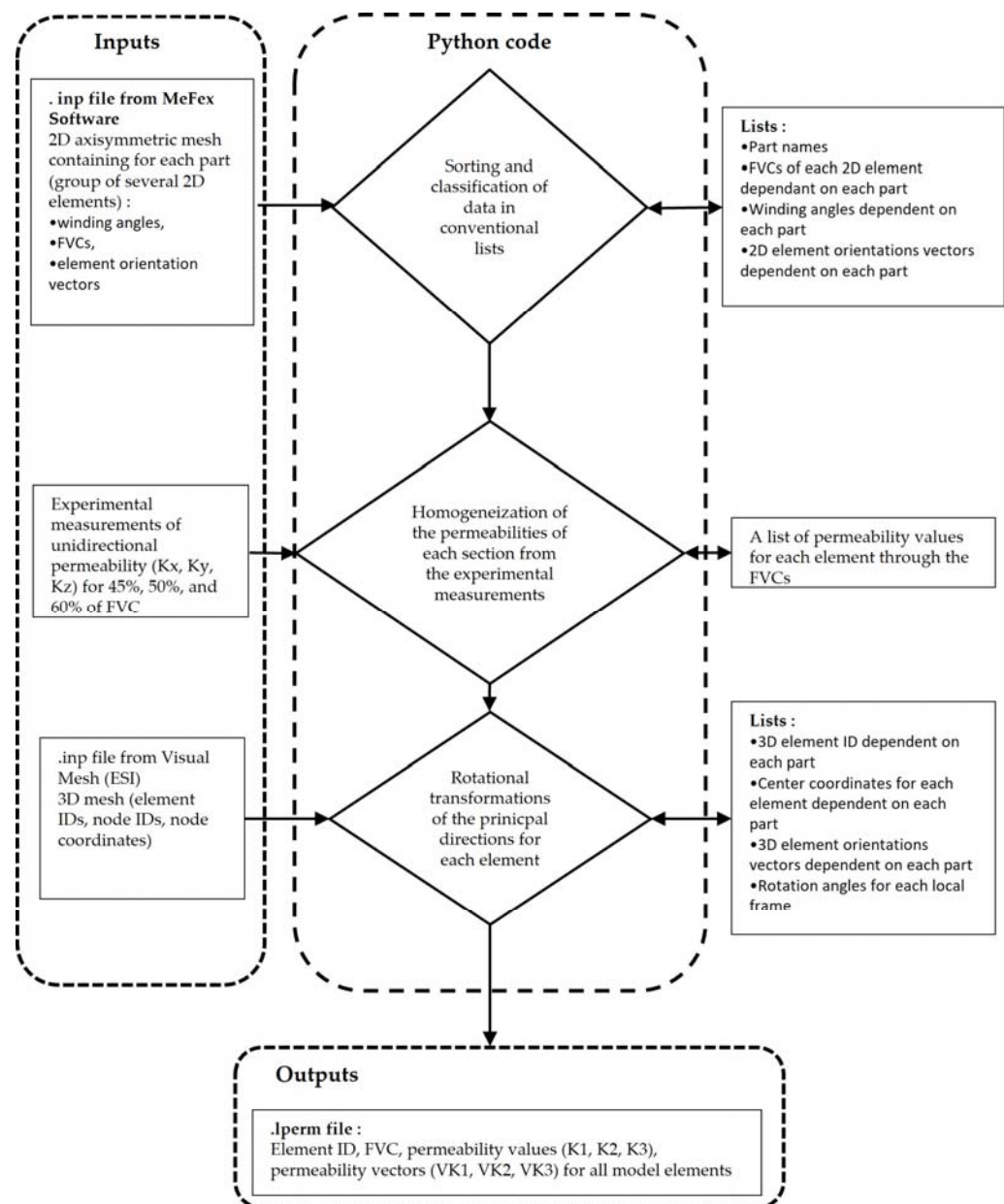


Figure 2. Architecture of the Python code for the calculation of each element's principal permeabilities. Physical inputs, functions, and physical outputs.

3.2. Importation of the .inp File Data, the Experimental Permeability Measurements, and the 3D Mesh File

The first step in the Python code is to import the .inp file from the filament winding software of mefex GmbH, Weiterstadt, Germany, version 0.95.3 (<https://mefex.de/>). This file contains all the mesh data and properties of an axisymmetric 2D model, such as mesh coordinates, winding angles, thicknesses, FVCs, and orientations of the local reference frame for each element. The permeabilities of a UD ply are measured experimentally at different FVCs and are interpolated with a polynomial interpolation for any FVC.

3.3. Reading and Sorting the .inp File Data into a List for Each 2D Section

The information in the MeFex .inp file is classified into groups of elements which share the same 2D axisymmetric properties. These groups are called sections or parts. The code goes through this .inp file to read and store the necessary properties and sort them in the

same sequence as the parts. Hence, the sequence of sections allows each 2D element to be linked to the properties of the section to which it belongs.

3.4. Homogenization-Diagonalization of the Permeability of the Stacking of Each Part, and Rotational Transformations of the Principal Directions for Each 3D Element

Each section consists of a stack of plies. Homogenization and diagonalization of the permeability described in Section 2 are implemented in the code for each section. The diagonalization is realized with the Python function called “np.linalg” from the “NumPy” library.

The principal permeabilities of each 3D element are calculated from those of the stacking of the 2D-axisymmetric section of elements from which it has been generated (by spinning the 2D mesh). The principal values are the same, but the principal directions must be rotated, as described in Section 2.6.

3.5. Writing of the .Iperm File

The permeability data were written in an “.Iperm file” which is the output of the permeabilities modelling approach. The Iperm file contains the principal permeabilities (values and directions), the FVC, and thickness for each 3D element (by element ID). This Iperm file is imported into the software Visual-RTM, included in Visual-Environment version 17.0, in which the cylindrical filament wound dry fibre preform is modelled for subsequent RTM simulation with PAM-RTM version 2021.0. Visual-Environment version 17.0 and PAM-RTM version 2021.0 are softwares from the ESI Group (part of Keysight Technologies since November, 2023), Bagneux, France.

3.6. Experimental Measurement of the Principal Values and Directions of Permeabilities for UD Stacking and Multidirectional Stackings

To calculate the local permeabilities of the cylindrical filament wound dry perform, experimental permeability measurements were made on a UD dry perform and also on multidirectional dry preforms. For convenience reasons, those preforms consisted of a stack of UD plies with different stacking sequences, and not of flat filament wound dry preforms, which would have been hard to make and to handle, for instance. However, the UD ply used in the stackings was made of the same fibre bundles as the UD tape used in the filament wound cylindrical dry preform. The measurements were carried out with the test bench Easyperm by Groupe Institut de Soudure, Saint-Avold, France. The permeability principal directions of a stacking correspond to the major and minor axes of the ellipse formed by the resin on top of the stacking and can therefore be measured experimentally. The permeability principal values are measured experimentally using the Darcy Law. The experimental measurements of permeabilities for the UD stacking were used as input for the model developed to predict the permeabilities of multidirectional stackings. Permeability measurements on multidirectional stackings were used for correlation with the model calculations and subsequent recalibration of the model. The FVC is related to the thickness of the stacking. The experimental range of FVC (45–60%) was chosen from the estimated FVC of a stacking before compression and from an estimate of the maximum FVC which could be reached by the test bench. This range of FVC is considered to cover values which can typically be reached in filament winding and the RTM process. For each FVC and stacking, five specimens were used for the in-plane principal permeability measurement (310×310 mm square samples), and five specimens were used for the out-of-plane permeability measurements (250 mm diameter disk samples). The permeability principal directions of a stacking were measured with one specimen.

The permeability principal directions and principal values at different FVCs were measured experimentally on the following stackings:

- $[0_{10}]$ at 45%, 50%, and 60% of FVC, for use as input for the model;

- $[60_5; -60_5]$ at 45%, 50%, and 60% of FVC, to see the impact of an interface involving a change in winding angle;
- $[60; -60]_5$ at 45% and 60% of FVC, to see the impact of several interfaces involving a change in winding angle;
- $[90; 80; -80; 72; -72; 65; -65; 60; -60; 56; -56]$ at 60% of FVC, to see the effect of the circumferential layer and to compare the results with the homogenization model;

Thus, the purpose of the choice of these stackings was to highlight the effect of the number of interfaces between plies of different orientations on the permeabilities, and the effect of nesting when it is significant (successive plies with the same orientation). The main way to prevent nesting is to vary the angle between successive plies, so that these plies do not interpenetrate each other. In the filament winding process, successive layers should have different winding angles to avoid nesting, which is usually the case. Nesting may also depend on fabric architecture, particularly the yarn packing density [17]. These measurements were important to investigate the effect of nesting on the permeabilities at the macroscopic level and to check the robustness of the modelling method.

4. Results

4.1. Visualization of the Computed Permeabilities Principal Directions

The principal directions of the permeabilities of each 3D element were computed with the Python code using geometrical projections from a 2D axisymmetric section cut. They could be imported into Visual-RTM and visualized in the Visual-Viewer, included in Visual-Environment version 17.0, after running pre-calculation with PAM-RTM version 2021.0, which is a software from the ESI Group (part of Keysight Technologies since November 2023), Bagneux, France. An example is given in Figure 3.

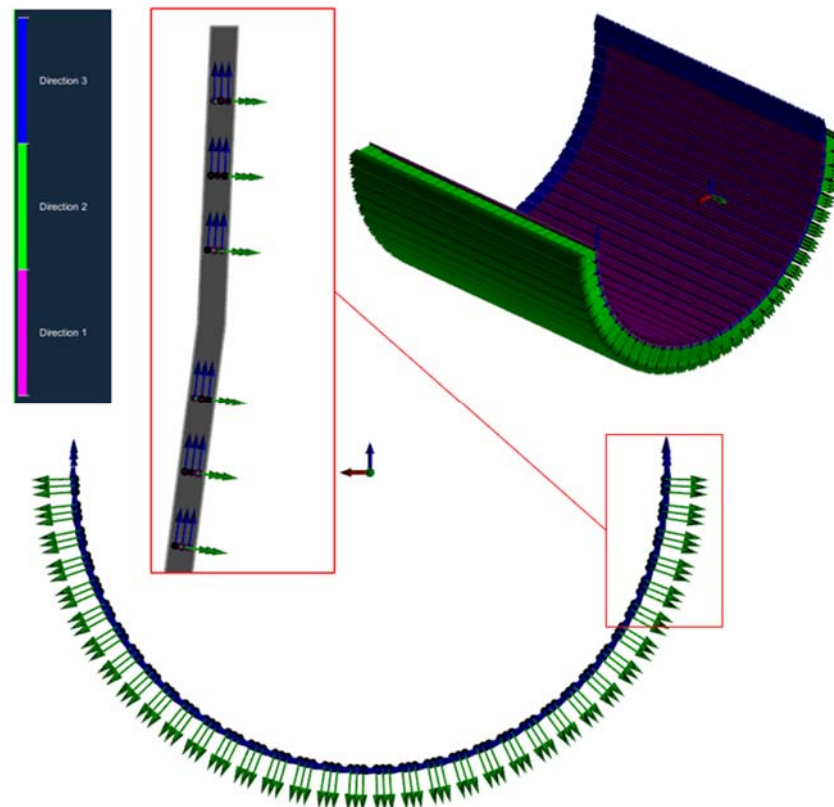


Figure 3. Computed principal direction of permeabilities. In-plane principal directions and out-of-plane (radial) direction are represented by vectors.

It is shown that the third principal direction (direction 2: green arrow) is normal to the cylindrical surface, and the in-plane principal directions (direction 1 and 3: blue and pink arrows) are tangential to the surface as expected. The principal angle θ can be verified to some extent. Helicoidal layers consist of two symmetrical plies. Thus, $\theta = 0$ if the multidirectional stacking is made of helicoidal layers only, whereas θ is not 0 if there is a circumferential layer in the multidirectional stacking. Thus, the range of angle variation for θ depends on the stacking sequences in the model.

4.2. Experimental Measurements of the Principal Permeabilities of the Stackings

The choice of the stacking sequences was justified in Section 3.6. For the UD stacking, experimental measurements have shown that the fibre direction and the in-plane direction perpendicular to the fibres are the principal directions. For the multidirectional stackings $[60_5; -60_5]$, $[60; -60]_5$ and $[90; 80; -80; 72; -72; 65; -65; 60; -60; 56; -56]$, the 0° direction and the 90° directions were measured as the principal in-plane longitudinal and transverse directions, respectively.

The principal values of permeabilities measured experimentally are given in Tables 1 and 2 for the different lay-up and at different FVC.

Table 1. Measured principal permeability values for the $[0_{10}]$ lay-up at different FVC.

Lay-Up	FVC (%)	K_i (m ²)	K_j (m ²)	K_k (m ²)
$[0_{10}]$	45%	2.0×10^{-10} ($\pm 41.3\%$)	7.9×10^{-11} ($\pm 32.3\%$)	3.5×10^{-13} ($\pm 30.9\%$)
$[0_{10}]$	50%	2.1×10^{-11} ($\pm 24.9\%$)	3.0×10^{-11} ($\pm 18\%$)	2.6×10^{-13} ($\pm 17.1\%$)
$[0_{10}]$	60%	1.5×10^{-12} ($\pm 17.6\%$)	1.6×10^{-11} ($\pm 19.5\%$)	/
$[0_{10}]$	58.7%	/	/	6.2×10^{-14} ($\pm 24.3\%$)

Table 2. Measured principal permeability values for different multidirectional lay-ups at different FVC.

Lay-Up	FVC (%)	K_i (m ²)	K_j (m ²)	K_k (m ²)
$[60_5; -60_5]$	45%	1.6×10^{-10} ($\pm 35.8\%$)	1.2×10^{-10} ($\pm 25.3\%$)	4.5×10^{-13} ($\pm 20.2\%$)
$[60_5; -60_5]$	50%	5.0×10^{-11} ($\pm 33.5\%$)	4.6×10^{-11} ($\pm 32\%$)	3.8×10^{-13} ($\pm 26.9\%$)
$[60_5; -60_5]$	60%	8.9×10^{-12} ($\pm 8.3\%$)	4.6×10^{-12} ($\pm 13.1\%$)	1.3×10^{-13} ($\pm 9\%$)
$[60; -60]_5$	45%	1.5×10^{-10} ($\pm 25.4\%$)	8.9×10^{-11} ($\pm 49.8\%$)	1.2×10^{-13} ($\pm 4\%$)
$[60; -60]_5$	60%	6.8×10^{-12} ($\pm 3.4\%$)	6.5×10^{-12} ($\pm 7.1\%$)	5.8×10^{-13} ($\pm 4.5\%$)
$[90; 80; -80; 72; -72; 65; -65; 60; -60; 56; -56]$	60%	4.7×10^{-12} ($\pm 5.3\%$)	3.1×10^{-12} ($\pm 14.6\%$)	1.4×10^{-13} ($\pm 6.2\%$)

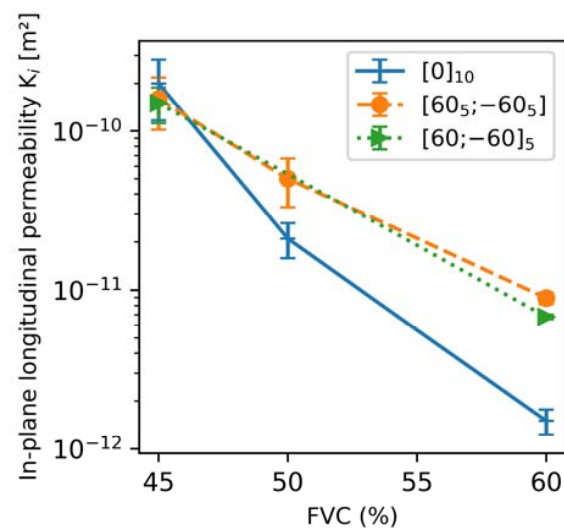
A synthesis of the permeability principal values measured is shown in Figures 4 and 5.

It is shown in Figure 4 that the permeability values in the three principal directions decrease as the FVC increases. If we compare the permeability values for the stackings $[60_5; -60_5]$ and $[60; -60]_5$, it is seen that K_i and K_j are very close, whereas K_k is different. It is also seen in Figure 5 that the out-of-plane principal permeability K_k tends to be slightly higher for the multidirectional stackings $[60_5; -60_5]$ and $[60; -60]_5$ than for the unidirectional stacking. These results are discussed in Section 5.

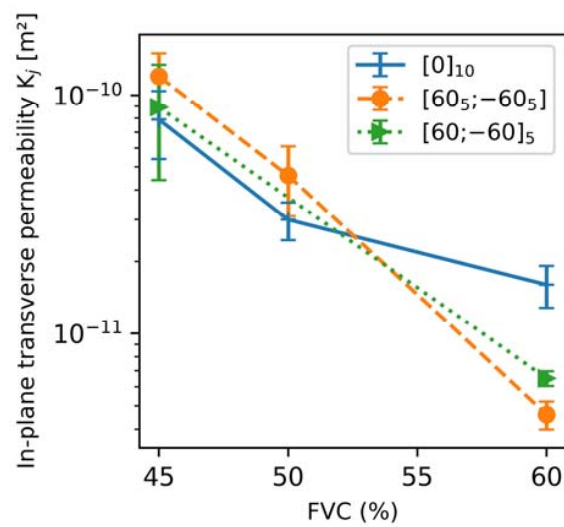
4.3. Comparison Between Computed Permeabilities and Measured Permeabilities

Experimental measurements were conducted with the aim of studying the impact of fibre compaction, the impact of interfaces between different plies ($[60_5; -60_5]$ and $[60; -60]_5$), and a validation stacking of the configuration most representative of the variations in angles due to filament winding ($[90; 80; -80; 72; -72; 65; -65; 60; -60; 56; -56]$).

Comparisons between the experimental and calculated permeabilities using the homogenization method are presented with the same fibre volume content (FVC) in Figures 6–8.



(a)



(b)

Figure 4. In-plane principal permeabilities as a function of the FVC for different stackings in (a) the i-direction and (b) the j-direction.

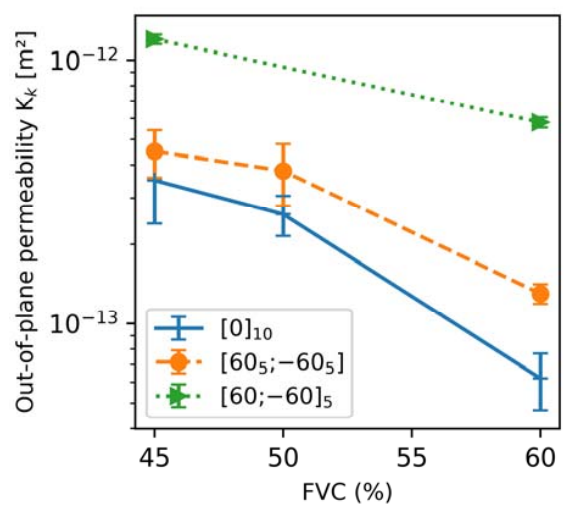
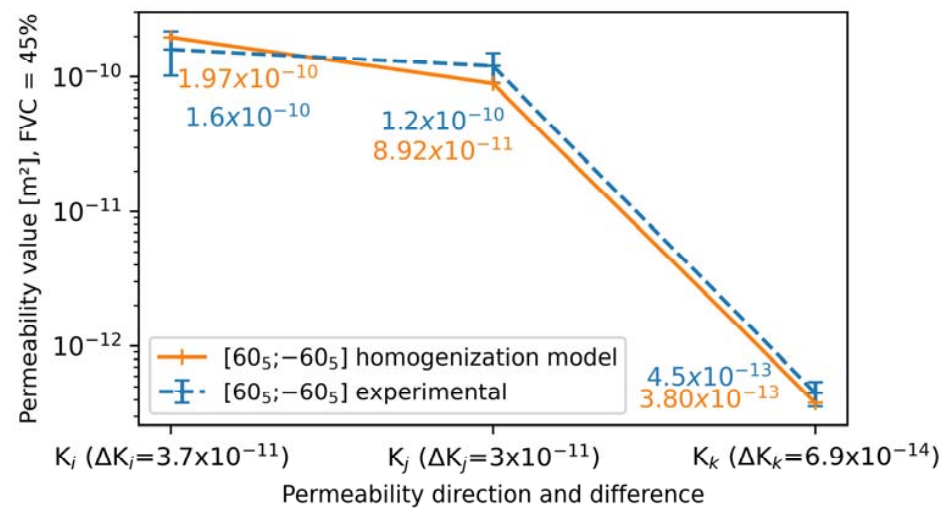
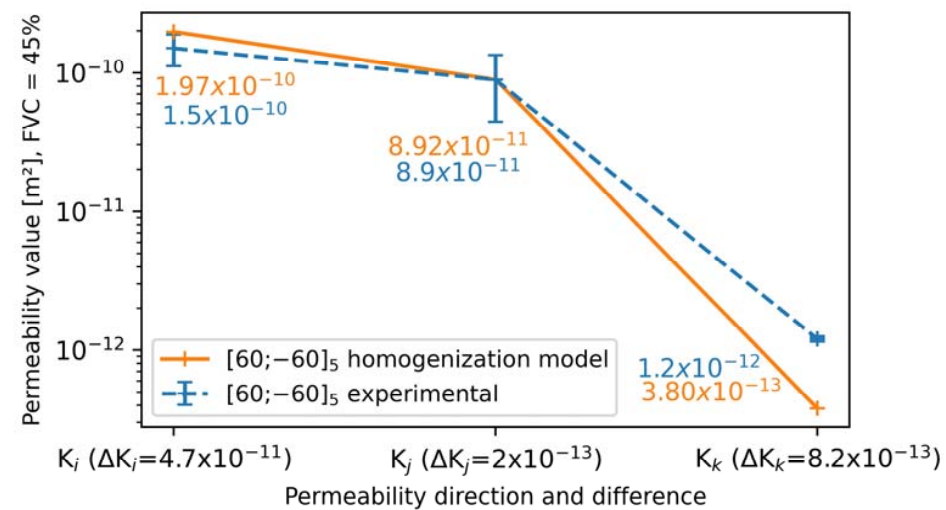


Figure 5. Out-of-plane principal permeabilities as a function of the FVC for different stackings.



(a)



(b)

Figure 6. Comparison between the calculated and measured principal permeability values for (a) the lay-up [60₅; -60₅] and (b) the lay-up [60; -60]₅ with 45% FVC.

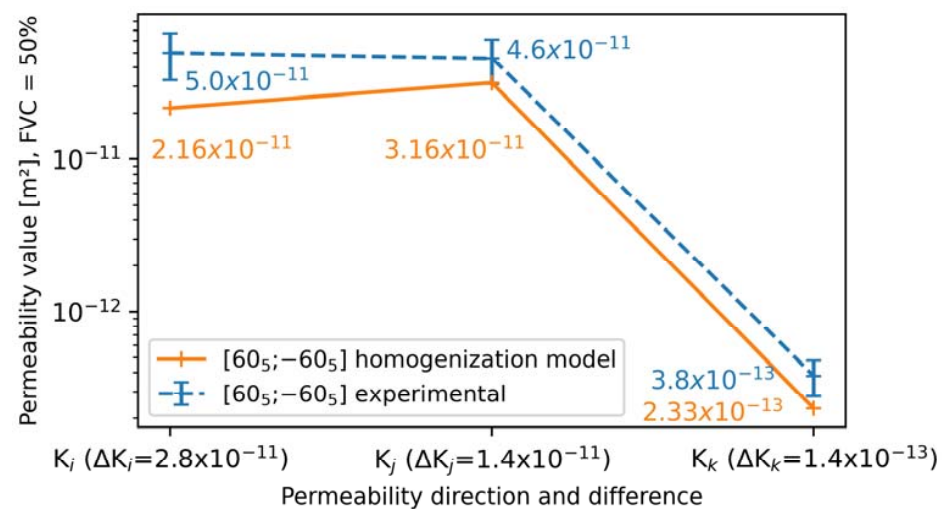
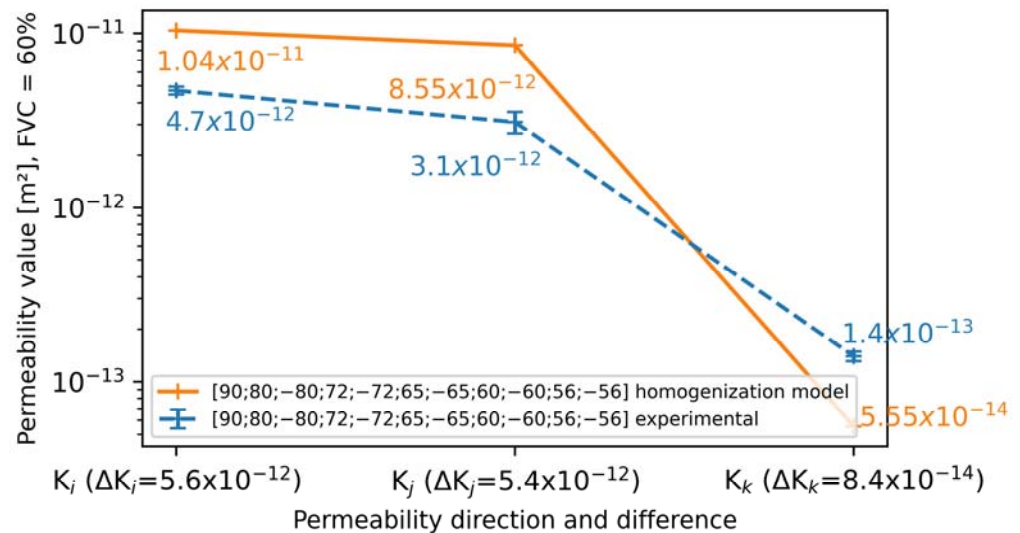
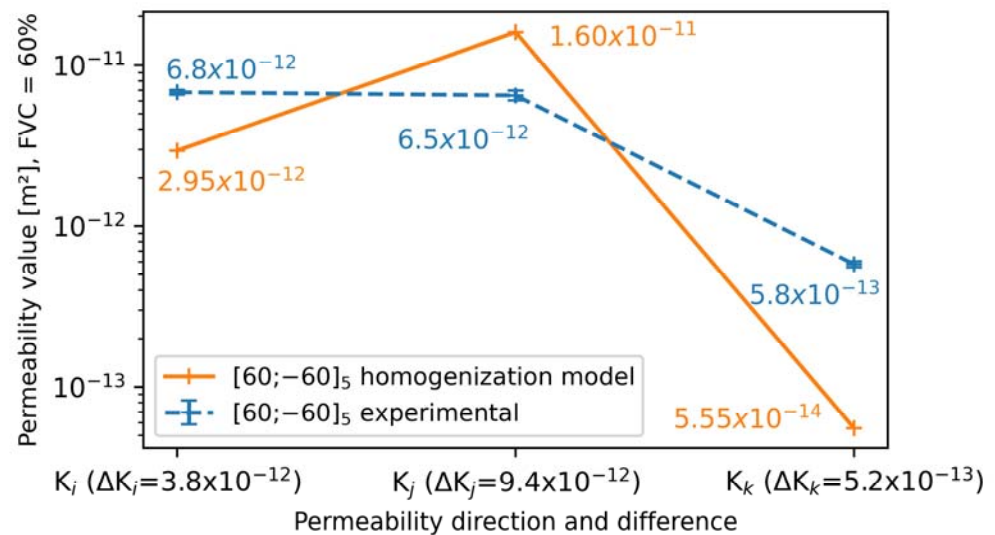


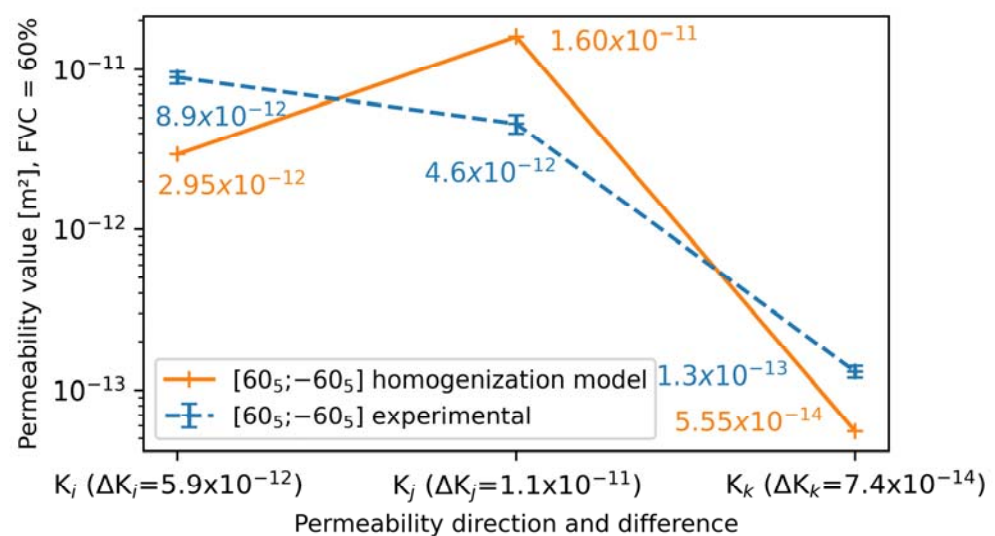
Figure 7. Comparison between the calculated and measured principal permeability values for the lay-up [60₅; -60₅] with 50% FVC.



(a)



(b)



(c)

Figure 8. Comparison between the calculated and measured principal permeability values for the lay-up [90; 80; -80; 72; -72; 65; -65; 60; -60; 56; -56] (a), [60; -60]₅ (b), and [60₅; -60₅] (c) with 60% FVC.

5. Discussion

5.1. Experimental Measurements of the Principal Permeabilities

The principal directions are the 0° and the 90° direction, as expected for the UD stacking. For the symmetric multidirectional stacking, these are also the principal directions, which are attributed to the fact that the stacking sequence is symmetric. However, for the unsymmetric stacking sequence, the one with the circumferential 90° layer, the principal direction was expected to be affected by the 90° circumferential layer. In practice, it might have very little effect as compared to the whole lay-up. It is located at the bottom of the stacking and the principal directions are rather observed at the top of the stacking. To highlight the effect of the 90° ply, the experiment might need to be conducted using the reversed stacking sequence, which was not performed for reasons of time and cost.

In Figures 4 and 5, the principal values of permeability tend to decrease with the FVC. The FVC is increased by out-of-plane compression of the stacking. Thus, the decrease in the principal permeability values with the FVC is attributed to a higher compaction of the reinforcement. The in-plane permeabilities and the out-of-plane permeability tend to be higher for the multidirectional stacking than for the UD stacking. This might be attributed to the effect of “nesting” in the UD stacking, which corresponds to the interpenetration of two adjacent UD plies sharing the same orientation and resulting in a more compact reinforcement. For the multidirectional stacking, there might be, on the contrary, a more “open” fibre network in the out-of-plane direction due to the interface between two plies of different orientation (which also prevents the “nesting” effect). Thus, the higher the number of these interfaces (stacking $[60; -60]_5$), the higher the out-of-plane permeability.

It is important to underline here that the experimental measurement of the permeabilities of the dry UD tape has been made on a stack of dry UD plies. This might have an impact on the nesting effect and thus on the model predictions, since the UD stacking permeabilities measurements are used as input in the model. To enhance the model accuracy, model recalibration based on multidirectional stackings with minimal nesting has been performed and is presented in Section 5.3.

5.2. Deviations Between Computed Permeabilities and Experimental Permeabilities

As expected, the comparison between calculated and experimental permeabilities seems to depend on the “nesting effect”. The UD permeabilities used as input data for the model were impacted by nesting. The nesting effect is expected to impact mainly the out-of-plane permeability. It might also impact the in-plane permeabilities at high FVC. The number of changing interfaces was expected to reduce the nesting effect since two adjacent plies with different angles cannot interpenetrate each other and are less compact. We note that the deviation is very similar for in-plane permeabilities, but it changes for the out-of-plane permeability. The out-of-plane permeability increases with the number of interfaces between plies of different orientations. Thus, the correlation between calculated and experimental permeabilities is better for the stacking $[60_5; -60_5]$, with only one changing interface compared to the stacking $[60; -60]_5$ with nine changing interfaces.

Regarding the principal directions of permeabilities, they were calculated for the stacking because it was not symmetric. The theoretical homogenization model calculates principal directions in the (x,y) plane which make a 25.9° angle with the experimental directions. In practice, the circumferential layer at 90° is located below the stacking and therefore has only a minor effect on the ellipse formed by the resin on top of the stacking, which defines the measured principal directions. This could also possibly explain little deviations in x and y permeability values, since for this stacking they are not measured exactly in the same directions.

5.3. Recalibration of the UD Tape Input Permeabilities Using Experimental Results of Stackings with Only Little Nesting Effect

A recalibration of the UD tape input permeabilities using experimental results of stackings with only a minor nesting effect can be offered. Experimental permeabilities were measured for the following three stackings:

- Stacking 1: [90; 80; −80; 72; −72; 65; −65; 60; −60; 56; −56] with 60% of FVC;
- Stacking 2: [60; −60]₅ with 45% and 60% of FVC;
- Stacking 3: [60₅; −60₅] with 45%, 50%, and 60% of FVC.

Minimum nesting is on the stacking 1 and stacking 2, with many changing interfaces, and the maximum nesting is obtained through stack 3, with only one changing interface. This is because stackings 1 and 2 have a different angle between the individual plies, which prevents nesting. Therefore, it might be more relevant to use them to recalibrate the input permeability values of the UD tape by using an inverse optimization method. This was performed at 60% FVC.

The statistical optimization method used to recalibrate the initial values of the UD tape consists of an inverse homogenization method, which minimizes the deviation between numerical and experimental results. The optimization algorithm used is the L-BFGS-B method, a quasi-Newton optimization algorithm that approximates the Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm using a limited amount of computer memory. Table 3 gives the experimental permeabilities measured on a UD stacking impacted by the nesting effect and the UD tape permeability values calculated with the inverse optimized method. There are no clear trends in the results since the experimental values might be higher or lower than the predicted values. This might be due to microscopic effects that counterbalance each other.

Table 3. New UD permeabilities obtained by the inverse optimization method using the combined permeability results of stacks 1 and 2.

Units		Experimental UD Permeabilities	Theoretical UD Permeabilities, Calculated from [3,4]	Calculated UD Permeabilities for Model Recalibration
FVC	%	60	60	60
K_i	m ²	1.50×10^{-12}	4.36×10^{-13}	5.00×10^{-13}
K_j	m ²	1.60×10^{-11}	3.86×10^{-14}	5.08×10^{-12}
K_k	m ²	6.20×10^{-14}	3.86×10^{-14}	2.85×10^{-13}

Using these calculated UD permeabilities as input, we can recalibrate the homogenization model for the stackings with a minor nesting effect: stackings 1 and 2. We see an improvement in the final results in Figure 9.

The grey curve “Recalibrated homogenization model” gives the results of the homogenization model with the calculated input values of the UD tape. The in-plane permeability values (K_i , K_j) given by the “Recalibrated homogenization model” are very close to those obtained by experimentation. The out-of-plane permeability (K_k) given by the “Recalibrated homogenization model” is also improved and closer to the experimental results.

However, there is still a slight difference with experimental values as shown in Table 4.

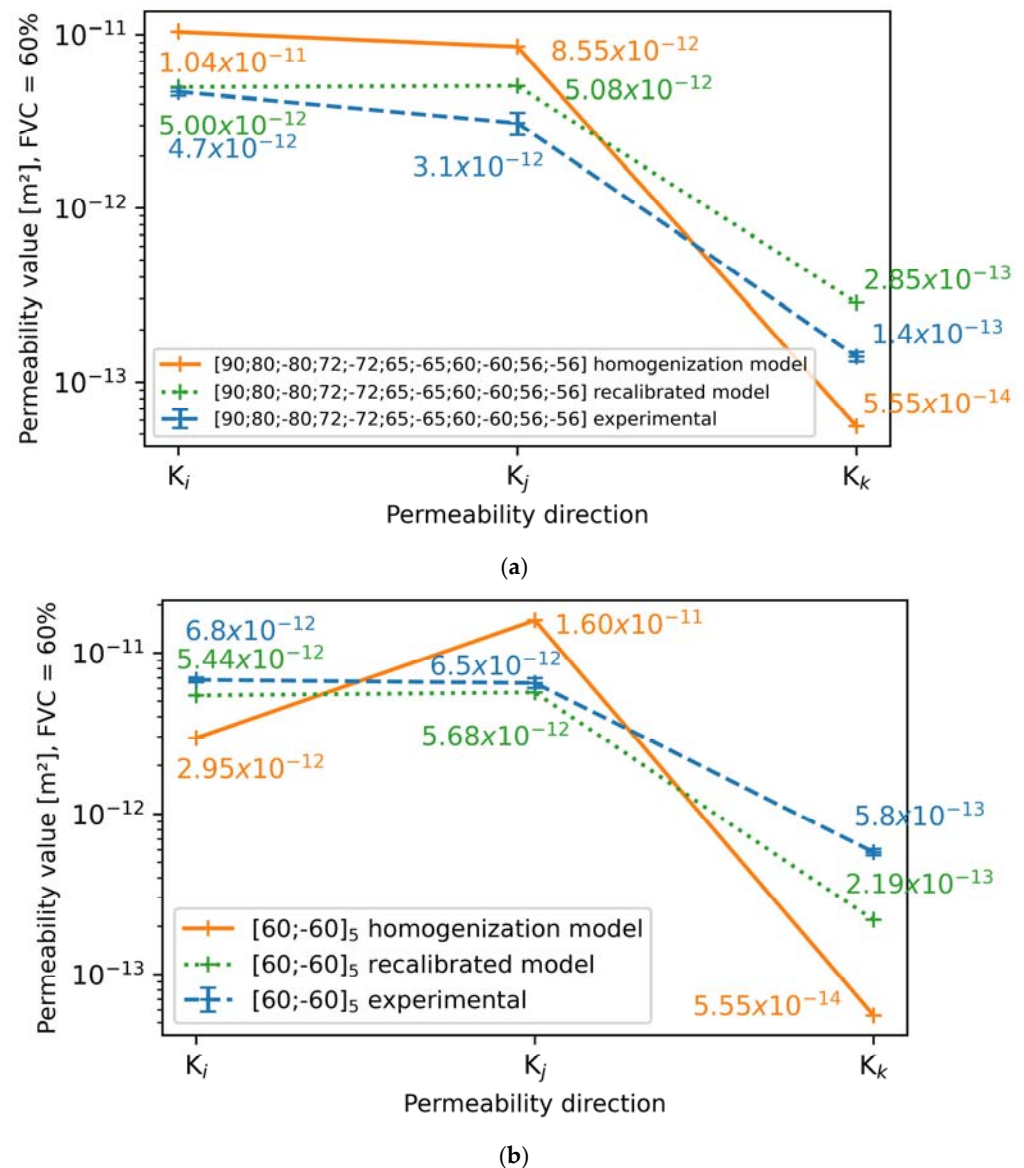


Figure 9. Comparison between the calculated permeabilities with experimental UD permeabilities, new UD permeabilities, and measured principal permeability values for (a) the stacking 1 and (b) the stacking 2 with 60% FVC.

Table 4. Difference between recalibrated homogenization model (B) and experimental permeabilities (A) at 60% FVC.

		B: Experimental Permeabilities (m ²)	Standard Deviation (SD) of Experimental Permeabilities (%)	A: Recalibrated Homogenization Model (m ²)	Absolute Value of Logarithmic Difference, [22,23], multiplied by 100%: $ \log A - \log B \times 100\%$	Absolute Value of Percentage Change: $\left \frac{A-B}{B} \right \times 100\%$
Stacking 1	K _i	4.7 × 10 ⁻¹²	5.3%	5.00 × 10 ⁻¹²	2.7%	6.4%
	K _j	3.1 × 10 ⁻¹²	14.6%	5.08 × 10 ⁻¹²	21.5%	63.9%
	K _k	1.4 × 10 ⁻¹³	6.0%	2.85 × 10 ⁻¹³	30.9%	103.6%
Stacking 2	K _i	6.8 × 10 ⁻¹²	3.0%	5.44 × 10 ⁻¹²	9.7%	20.0%
	K _j	6.5 × 10 ⁻¹²	7.0%	5.68 × 10 ⁻¹²	5.9%	12.6%
	K _k	5.8 × 10 ⁻¹³	5.0%	2.19 × 10 ⁻¹³	42.3%	62.2%

This difference is attributed to microscopic effects at the interface between each ply, since the model presented in this paper is rather macroscopic. It homogenizes local stacking

properties at the local laminate level. It could be suggested that even better correlation might be obtained using more experimental data for recalibration of the UD tape permeabilities. In addition, the recalibration uses an optimization method that finds a local optimum based on the UD permeabilities affected by nesting as a starting point. Further investigation might be performed in future work to find a global optimum on a wider range of inputs for the UD permeabilities.

5.4. Evaluation of the Modelling Approach

The calculation time of the Python code depends on the number of elements in the mesh. For example, if the mesh contains about a million elements and several thousands of parts (sections with different stacking sequences), the calculation time of the principal permeabilities of each element could be in the order of 20 min. This allows significant savings in terms of development time as compared to a purely experimental approach which would be hard to consider for this number of stackings.

In addition, the Python code provides the principal permeabilities of stackings without the cost of experimental measurements. The modelling approach is flexible because it only depends on the input permeabilities of UD fibres, and not on a particular winding scheme. Different winding schemes can be treated quickly, which is advantageous in terms of development.

In terms of accuracy, the advantage of this modelling approach lies in the fact that it calculates local permeabilities, for each element of the mesh, and considers the local stacking sequences. A limitation of the modelling approach is that it does not take into account size effects and side effects in the resin flow. However, this might significantly complicate the approach and might be investigated in future research.

6. Conclusions

A modelling approach has been presented to calculate the local principal permeabilities of cylindrical of filament wound dry preform for RTM simulation. This model is based on the principal permeabilities of the dry UD tape which are used as input, and it is used to predict the permeabilities of local multidirectional stackings in the filament wound preform. The permeabilities of the UD tape are measured in a first step using a flat UD stacking.

Comparisons between experimental and calculated permeabilities of various multidirectional stacking sequences revealed significant effects of the *FVC* and of the “nesting” phenomenon on both in-plane and out-of-plane permeability values. It was observed that principal permeabilities decrease with increasing *FVC* due to higher reinforcement compaction. The in-plane and out-of-plane permeabilities were significantly higher in multidirectional stackings compared to UD stackings, attributed to the nesting effect in UD stackings leading to a more compact reinforcement.

It was noted that deviations between calculated and experimental permeabilities are more pronounced in stackings with multiple changing interfaces where there is no nesting. This indicates that the nesting effect influences the accuracy of permeability predictions. This accuracy is influenced by the UD input permeabilities, which experienced significant nesting and compaction, making them less representative for multidirectional stacking in which there is no nesting.

Recalibration of the UD tape permeabilities used as input in the model was performed using experimental data from stackings with minimal nesting effects. This recalibration, achieved through an inverse homogenization and optimization method, yielded new UD permeability values that improved the alignment of model predictions with experimental results. Specifically, the recalibrated homogenization model demonstrated improved accuracy for in-plane permeabilities and a closer match for out-of-plane permeability, although

slight discrepancies remain due to microscopic interfacial effects and some coupling effects between flow directions. This modelling method opens the way for a multi-scale modelling approach which would be based on elementary volumes.

The model developed is quite simple and runs quickly. It predicts local principal permeabilities in a filament wound dry preform and can be used on a large numerical model for RTM simulation. The impact of any discrepancies at the local level on the global scale is minimized, ensuring the overall reliability and effectiveness of the permeability predictions. Applicable areas of the proposed approach might include any cylindrical structural composites made with dry filament winding and the RTM process. This approach reduces the amount of experimental measurements needed, which also lowers the cost and time of development.

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Abbreviations

The following abbreviations are used in this manuscript:

UD	Unidirectional
FVC	Fibre Volume Content
RTM	Resin Transfer Moulding

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