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Published in:
Proceedings of ECCM21 – 21st European Conference on Composite Materials

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Laborderie, L. M., Pierce, R. S., & Haselbach, P. U. (2024). A spacing criterion for perforated release films in vacuum-assisted resin infusion processes. In Proceedings of ECCM21 – 21st European Conference on Composite Materials

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A SPACING CRITERION FOR PERFORATED RELEASE FILMS IN VACUUM-ASSISTED RESIN INFUSION PROCESSES

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Keywords: vacuum infusion, resin flow, perforated release film, spacing criterion, homogenisation

Abstract

Vacuum infusion processes often use perforated release films as an interlayer between the resin distribution media and the fabric to help separate the infusion consumables from the final composite part. Guidelines are developed in this work for choosing a release film with an appropriate perforation pattern to produce a homogenous flow behaviour. A spacing criterion is derived analytically and provides the maximum allowable distance between the perforations to minimise the risk of introducing voids or dry spots. The criterion relies physically on the fabric permeability and the stack thickness. When the spacing criterion is met, the perforated release film can be homogenised for modelling purposes, an essential simplification for computational efficiency and large-scale simulations. A coupled analytical-numerical method is also presented to evaluate the equivalent through-thickness permeability of the homogenised release film in support of modelling. Preliminary infusion experiments and numerical simulations performed at the unit cell scale in PAM-RTM offer initial validation for the spacing criterion and the homogenisation method, although the current formulation of the criterion is expected to be quite conservative.

1. Introduction

Vacuum Assisted Resin Infusion (VARI) is a composite manufacturing process commonly used for wind turbine rotor blades, where dry reinforcements are placed on a rigid half-mould and sealed by a flexible vacuum bag. Liquid resin flows through and impregnates the reinforcement lay-up, driven by the pressure difference between the inlet – typically at atmospheric pressure – and the outlet – connected to a vacuum pump. The lay-up classically consists of dry layers of fibrous reinforcements but can also include core materials or pre-cast elements. A resin flow-enhancing distribution mesh is often used to top the lay-up and reduce the filling time. This requires an interlayer (typically peel-ply, perforated release film, or both) is used to ensure easy removal of the distribution mesh from the cured laminate. Peel-ply is a woven and permeable product that increases resin consumption and waste but leaves a rough surface suitable for further adhesion processing. Alternatively, perforated release films have a much lower resin uptake, as they are impermeable membranes with a pattern of tiny discrete perforations that allow for through-thickness resin transfer. Despite different perforation patterns being available commercially, there appear to be no openly available recommendations to indicate which pattern is adequate for a given application. This work aims to formulate guidelines for choosing a suitable perforation pattern for any specific application based on the lay-up properties (stack height and anisotropic fabric permeability) in order to reduce the risk of manufacturing-induced voids. Additionally, since the simulation of each perforation hole is not feasible for macro-scale or blade-scale simulations [1] a method is also presented to include the release film in numerical simulations as a homogeneous porous material, instead of an impermeable membrane with discrete perforations.

2. Theoretical spacing criteria

Since the release film is a perforated membrane with a typical perforation pattern as illustrated in Figure 1, it can be represented by a repeated rhombus-shaped unit cell consisting of a single hole per unit cell [2]. The repeating 2D unit cell can then be characterized by the hole diameter d, and its geometry. The spacing parameters s_x and s_y refer to the half-diagonals of the rhombus unit cell. The convention to describe the spacing parameters is defined in Figure 1.

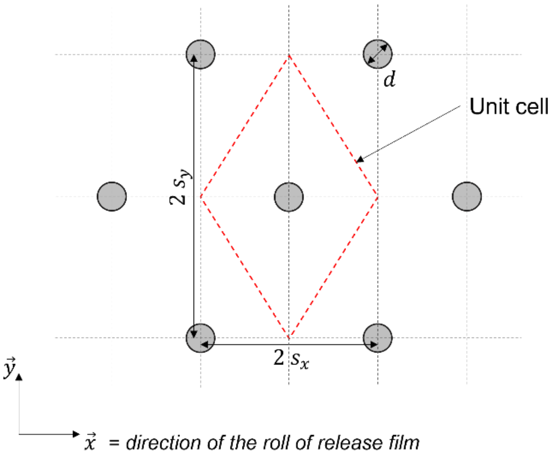


Figure 1. Perforated release film unit cell and definition of the spacing parameters s_x and s_y.

The perforations convert the resin flow from 1D (or 2D in-plane) in the distribution media to a 3D flow in the fabric. Indeed, each perforation acts as a distinct inlet for radial infusion. The case of one circular inlet on the surface of a fabric stack for radial three-dimensional flow has been studied extensively, with analytical models, numerical simulations and experimental measurements [3, 4, 5, 6] in most cases with the specific aim of measuring fabric permeability.

From each perforation, an ellipsoidal flow front propagates in the fabric. As the ellipsoids grow, they start merging together. Depending on the 3D unit cell geometry (spacing parameters s_x and s_y and thickness of the fabric stack h) and on the fabric permeability (i.e. the shape of the ellipsoids), a dry area within the unit cell might be shut off from the outlet. This would lead to higher risks of dry spots and voids [7]. A suitable choice for the perforation pattern of the release film would be designed to avoid that situation.

The development of the spacing criteria focuses on the flow front shape for the time at which the flow front (emerging from the perforation within a given 3D unit cell) first reaches the bottom of the fabric stack. The neighbouring perforations and flow fronts/unit cells are neglected, along with the interactions between them.

If the fabric stack thickness h is sufficiently large, compared to the perforation diameter d, the latter does not influence the flow front shape when the bottom of the fabric stack is first reached [4]. For a typical composite application, where $d < 0.5\,mm$ and $h > 2\,mm$, it is reasonable to then ignore the perforation diameter for the purpose of this spacing criteria. The flow front shape in the fabric at that time can therefore be described with an ellipsoidal equation:

$$\frac{(x\cos\theta + y\sin\theta)^2}{h^2}\frac{K_3}{K_1} + \frac{(x\sin\theta - y\cos\theta)^2}{h^2}\frac{K_3}{K_2} + \frac{z^2}{h^2} = 1 \tag{1}$$

Here (x, y, z) are the coordinates of the flow front, where the $\vec{x}$ and $\vec{y}$ axis are defined in Figure 1, z is the depth of the flow front into the fabric. The origin of the coordinate system is at the centre of the perforation hole. θ is the angle between the fabric principal permeability K_1 and the $\vec{x}$ axis.

The ellipsoidal flow front crosses the vertical wall boundaries of the unit cell at a depth $z_c\left(x, y(x, s_x, s_y)\right)$. It can be demonstrated that z_c has four local minima at the four edges of the unit cell. An arbitrary coefficient $\alpha \in]0;1[$ is introduced, with the purpose of finding the spacing parameters s_x and s_y satisfying the condition $z_c > \alpha h$. After some simplifications and consideration of upper bounds for Equation (1), the following sufficient condition is obtained:

$$s_x < h\sqrt{1-\alpha^2}\sqrt{\frac{K_2}{K_3}} \qquad \text{and} \qquad s_y < h\sqrt{1-\alpha^2}\sqrt{\frac{K_1}{K_3}} \tag{2}$$

This formulation for Equation (2) is valid regardless of the orientation of the fabric compared to the perforation grid. The coefficient α was set to 0.9, ensuring that the fluid penetrates at least 90% of the way through the fabric at the walls by the time it fully penetrates the fabric in the middle of the unit cell. This choice provides satisfactory results for ensuring that no dry area in the unit cell is shut off from the outlet.

3. Thickness transformation and homogenisation of release film

For discrete numerical modelling of fluid flow through the perforated release film, only the perforation hole is represented as a fillable domain. In the case of a Darcy-based solver like PAM-RTM, it can be treated as a cylinder that must be defined as a porous material, with 100% porosity. Its height is the release film thickness, and its radius is that of the perforation. The through-thickness permeability can then be calculated by equating Darcy's flow rate to the flow rate obtained from Poiseuille's law for viscous laminar flow in a capillary tube of circular cross-section [8]:

$$K_{3,\text{hole}} = \frac{r^2}{8} = \frac{d^2}{32} \tag{3}$$

One challenge for modelling the release film is that it is usually relatively thin compared to the thickness of the other components involved. For example, both release films considered in this study were about 0.03 mm thick, whereas the fabric stack and flow mesh thicknesses were closer to 0.5 to 1.0 mm each. From a computing perspective, this presents a significant problem for mesh quality, especially in the case of macro-scale 3D simulations [1]. Thus, the following thickness transformation scheme has been implemented, where the $*$ subscript refers to the transformed parameter. For conservation of the pore volume, the porosity ϕ should be changed:

$$\phi^* h^* = \phi h \tag{4}$$

The through-thickness permeability K_3 also needs to be updated to match the filling time from Darcy's law (with and without thickness modification):

$$\frac{h^*}{K_3^*} = \frac{h}{K_3} \tag{5}$$

The remaining in-plane permeability values are updated with Equation (6) written in the 1 and 2 directions:

$$\frac{\phi^*}{K_i^{\,*}} = \frac{\phi}{K_i} \tag{6}$$

Additionally, to eliminate the need for modelling each individual perforation, it is convenient to consider the release film as a homogeneous porous material of the same thickness h_{RF} with porosity ϕ_{RF}:

$$\phi_{\text{RF}} = \frac{\pi(d/2)^2}{2 s_x s_y} \tag{7}$$

Here, it is only the release film perforation parameters s_x, s_y, and d that are necessary to determine the homogenised porosity.

However, the through-thickness permeability of the homogenised release film, $K_{3\,RF}$, cannot be simply calculated as the arithmetic average of the hole permeability, as in Equation (3), and the membrane permeability (which is considered to be 0). Indeed, studies revealed that the Arithmetic Averaging scheme is not accurate when the difference in permeabilities is high [9, 10, 11]. Instead, a coupled analytical-numerical method is proposed.

The filling time for 1D-flow through different materials in series is first expressed analytically based on Darcy's law:

$$t_{fill} = \frac{\eta}{2\Delta P} \sum_{i=1}^{n} \left(\frac{\Phi_i}{K_{3,i}} l_i^2 + 2 l_i \Phi_i \sum_{j<i} \frac{l_j}{K_{3,j}} \right) \tag{8}$$

In the present case, a series of three materials ($n = 3$) is considered: the flow mesh (FM), the homogenised release film (RF), and the fabric (fab). The through-thickness permeability of the homogenised release film is extracted from Equation (8):

$$\begin{aligned} K_{3,RF} = {} & \left[K_{3,FM}\ K_{3,fab}\ \eta\, h_{RF} \left(h_{RF}\Phi_{RF} + 2\,\Phi_{fab} h_{fab}\right)\right] \\ & \cdot \left[2\, K_{3,FM} K_{3,fab}\, t_{fill}\, \Delta P - K_{3,FM}\, \eta\, h_{fab}^2 \Phi_{fab} - K_{3,fab}\, \eta\, h_{FM}^2 \Phi_{FM} \right. \\ & \left. - 2\, K_{3,fab}\, \eta\, h_{FM}\, h_{RF}\, \Phi_{RF} - 2\, K_{3,fab}\, \eta\, h_{FM}\, h_{fab} \Phi_{fab}\right]^{-1} \end{aligned} \tag{9}$$

Then, the filling time t_{fill} of the perforated unit cell is obtained through numerical simulation, with a given pressure gradient ΔP, and viscosity η. Those parameters are inserted in Equation (9), along with the other material parameters, to calculate $K_{3,RF}$.

4. Results and discussion

4.1 Application of the spacing criteria

The spacing criterion presented in Equation (2) is an attempt to provide guidelines for choosing a release film with a perforation pattern that minimises the risk of introducing voids and dry spots in the laminate, when the fabric permeability is known. For a given stack height, the criterion defines critical spacing parameters, which can also be seen as the critical unit cell geometry: perforations patterns with a unit cell larger than the critical value have higher risk of introducing voids in the laminate. A visual representation of the criterion is given in Figure 2 for $\alpha = 0.9$, and different fabric stack heights. The spacing parameters of two commercially available release films are reported in the graph and in Table 1. Different types of fabrics were considered in the study, but only one is presented in this paper, with permeability properties: $K_1 = K_2 =$ 5E-11 m^2, and $K_3 =$ 4E-12 m^2. The permeability ratio is reported in the graph in Figure 2. A reading of Figure 2 gives that for the infusion of a 3 mm-stack of this fabric, the spacing criterion is met for all release films with spacing parameters s_x and s_y smaller than 4.6 mm. When comparing the two commercial release films, Figure 2 shows that only one of them meets the criterion (MP22). The release film P3 only meets the criterion for a 7 mm-stack of that fabric.

Table 1. Spacing parameters of two commercially available release films.

Commercial release film	Spacing parameter (mm) s_x	s_y
MP22	1.5	1.5
P3	10	5

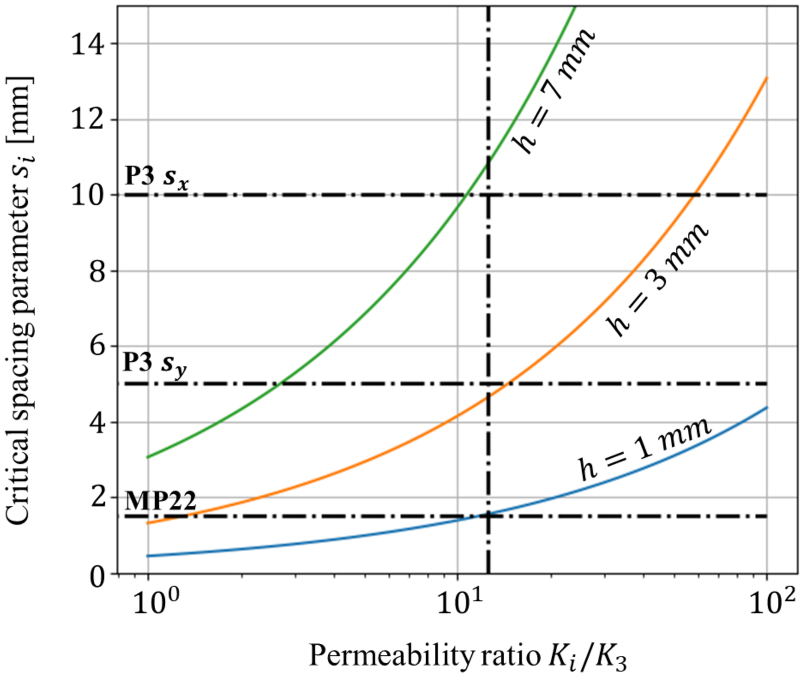


Figure 2. Maximum spacing as a function of the permeability ratio, for different fabric stack thickness h and parameter $\alpha = 0.9$. For the infusion of a 3 mm-stack of fabric with permeability ratio $K_1/K_3 = K_2/K_3 = 12.5$, release films with spacing parameters smaller than 4.6mm meet the spacing criterion. This is the case for the MP22 perforation style, but not for P3.

4.2 Numerical validation of release film homogenisation

In order to assess the performance of the homogenisation scheme, the filling times of a perforated unit cell and its homogenised counterpart are compared. A filling simulation is performed in PAM-RTM for the perforated and the homogenised unit cells from the MP22 release film. Its spacing parameters as defined in Figure 1 are $s_x = s_y = 1.5\,mm$. A 3 mm stack of fabric is used, with a layer of distribution media sitting on top of the release film. The filling times resulting from the simulations are reported in Figure 3.

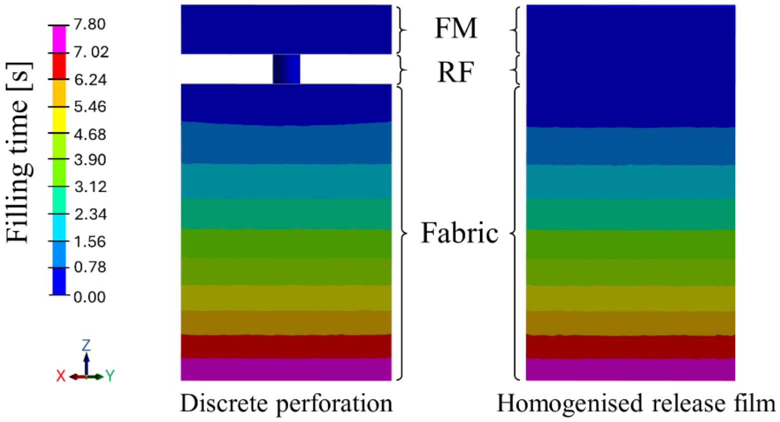
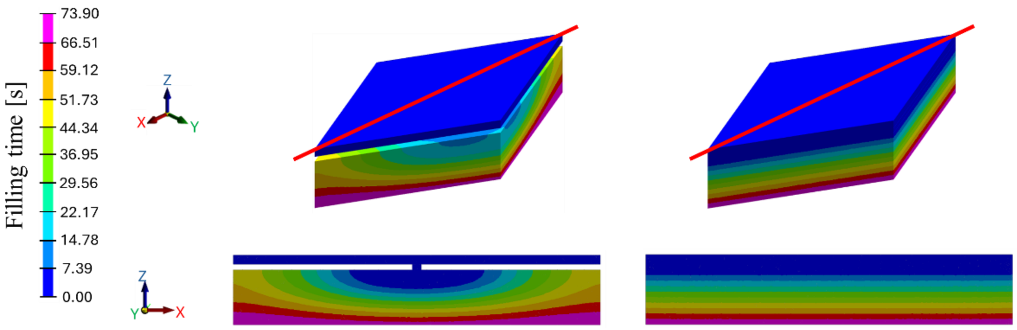


Figure 3. Filling times obtained from the simulation of the perforated MP22 unit cell. The different colours stand for the time at which the flow front has reached a specific point. The flow front shape at a specific time is given by the isolines.

The α parameter, introduced in Equation (2), can also be interpreted as a flatness tolerance describing how flat the (ellipsoidal) flow front is within the unit cell. As the unit cell in Figure 3 meets the spacing criterion from Equation (2) and Figure 2, the flow front is expected to be flat when reaching the bottom of the fabric stack. This prediction aligns with the flow front shapes displayed in Figure 3. The filling time of the perforated unit cell obtained numerically is inserted in Equation (9) along with the different material and process parameters in order to calculate the through-thickness permeability of the homogenised release film for this specific material configuration. A filling simulation of the homogenised unit cell is then performed, with the same process parameters. The results are shown in Figure 3. The filling times of both the perforated and homogenised unit cell match (0.13% relative difference), and so do the flow front displacements within the fabric.

The same process is repeated on a 3mm stack of fabric, with the P3 release film (the unit cell spacing parameters are $s_x = 10\ mm$ and $s_y = 5\ mm$). A reading of Figure 2 gives that this configuration does not meet the spacing criterion. This is in agreement with the observations made in Figure 4: the flow front shape in the perforated unit cell cannot be considered flat, and in turn, although the filling time of the homogenised unit cell indeed matches that of the perforated unit cell (with 0.63% relative difference), the flow front displacements in the fabric are significantly different.



Discrete perforation

Homogenised release film

Figure 4. Filling times obtained from the simulation of the perforated P3 unit cell. The different colours stand for the time at which the flow front has reached a specific point. The flow front shape at a specific time is given by the isolines.

From these results, it can be concluded that the spacing criterion introduced in Equation (2) and Figure 2 also provides a validity framework for the homogenisation method (Equation (9)), in addition to indicating which perforation patterns have a lower risk of introducing voids and/or dry spots. It should be noted that the computed through-thickness permeability of the homogenised release film is specific for the given combination of release film and fabric. With a different fabric, a new computation is always required.

4.3 Preliminary experimental validation of spacing criteria

Preliminary experiments were carried out with a biaxial non crimp fabric. This fabric was similar to the one used in Section 4.1: for the infusion a 3mm-stack of this fabric, the release film MP22 theoretically meets the criterion, whereas the perforation style P3 does not. Vacuum infusions of 3 mm stacks of fabric were performed with identical process conditions, the only difference between the two cases being the release film perforation pattern (P3 and MP22). This single difference clearly results in two very different flow front behaviours depicted in Figure 5. With the P3 release film, the resin impregnates the fabric via multiple isolated flow fronts based on the far-spaced perforations, which generally converge later as the infusion continues but leaving visible “weld lines” where the flow converges and does not completely saturate the fabric. This peculiar flow front shape does not qualify for homogenising the release film in any potential flow modelling. This was predictable, as this configuration does not meet the spacing criterion. Alternatively for the MP22 release film in Figure 5, a relatively uniform flow front is obtained due to the closer spacing between perforations. This case fits the spacing criterion, and the uniform shape of the flow front intuitively allows for the homogenisation of the release film in any similar flow models. These preliminary experiments therefore corroborate the link between the spacing criterion and the applicability of the homogenisation scheme for simulation.

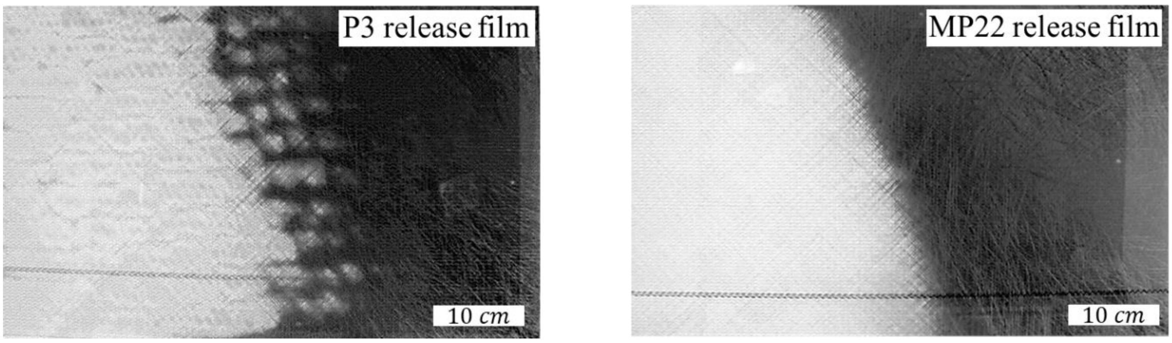


Figure 5. Different flow front shapes during infusions due to different perforation pattern of the release film.

5. Conclusions and future work

An innovative spacing criterion is derived analytically to provide guidelines for choosing a release film with a suitable perforation pattern for the infusion of a stack of fabric based on the fabric permeability and the stack height. In addition to indicating which perforation pattern minimizes the risk of manufacturing-induced voids, the spacing criterion also provides a validity framework for homogenising the release film via the coupled numerical-analytical method presented in this work. Both the spacing criterion and the homogenisation method are validated by numerical simulations and preliminary experiments. Despite its success, there is still significant potential for further improvement. Firstly, it does not account for the interactions between neighbouring unit cells, which makes it overly conservative. Although generally justified for most cases, any effect from the perforation diameter is currently ignored. A tri-dimensional version of the criterion accounting for those interactions is currently being developed, along with experimental validation. The results are to be presented in a later work.

Acknowledgements

We gratefully acknowledge the support and funding provided by the Innovation Fund Denmark for the AIOLOS project - "Affordable and Innovative Manufacturing of Large Composites" (Grant Number: 0224-00003B). Without this financial support, this research would not have been possible.

References

[1] R. S. Pierce. Challenges in permeability characterisation for modelling the manufacture of wind turbine blades. In *IOP Conference Series: Materials Science and Engineering*, 2023.

[2] V. Payo. Airtech Europe - Online catalogue. 2019. [Online]. Available: https://catalogue.airtech.lu/product_estore.php?product_id=1799&lang=EN.

[3] J. Weitzenböck, R. Shenoi and P. Wilson. Measurement of three-dimensional permeability. *Composites Part A: Applied Science and Manufacturing*, volume 29(1-2), pp. 159-169, 1998.

[4] S. Mekic, I. Akhatov and C. Ulven. A radial infusion model for transverse permeability measurements of fiber reinforcements in composite materials. *Polymer composites,* volume 30(7), pp. 907-917, 2009.

[5] F. Hurtado, A. Kaiser, A. Viedma and S. Díaz. Numerical analysis of the vacuum infusion process for sandwich composites with perforated core and different fiber orientations. *Journal of Sandwich Structures & Materials,* volume 18(4), pp. 415-444, 2016.

[6] P. Nedanov and S. Advani. A method to determine 3D permeability of fibrous reinforcements. *Journal of composite materials,* volume 36(2), pp. 241-254, 2002.

[7] N. Pearce, F. Guild and J. Summerscales. A study of the effects of convergent flow fronts on the properties of fibre reinforced composites produced by RTM. *Composites Part A: Applied Science and Manufacturing,* volume 29(1-2), pp. 141-152, 1998.

[8] T. Wu. Permeability prediction and drainage capillary pressure simulation in sandstone reservoirs. Texas A&M University, 2004.

[9] S. Bancora, C. Binetruy, S. Advani, E. Syerko and S. Comas-Cardona. Effective permeability averaging scheme to address in-plane anisotropy effects in multi-layered preforms. *Composites Part A: Apllied Science and Manufacturing,* volume 113, pp. 359-369, 2018.

[10] V. Calado and S. Advani. Effective average permeability of multi-layer preforms in resin transfer molding. *Composites science and technology,* volume 56(5), pp. 519-531, 1996.

[11] D. Seong, K. Chuang, T. Kang and J. Youn. A study on resin flow through a multi-layered preform in resin transfer molding. *Polymers and Polymer Composites,* volume 10(7), pp. 493-510, 2002.