Layup influence on the cured ply thickness of a composite material manufactured by the vacuum infusion process

Luís Alves
luis.f.alves@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

December 2021

Abstract

The vacuum infusion process is a manufacturing technique used in several industries with a wide range of part applications. One of its main drawbacks is the lack of thickness prediction models that accurately predict the cured part thickness distribution. Wind turbine blades suffer from this concern, and projects can be jeopardised if the design of the production process does not deliver parts within proper safety limits. This work aims to mitigate this problem and find alternative solutions instead of the current predictive methodologies applied. The goal is to develop an analytical model capable of predicting cured parts thickness focusing on more problematic blade areas. This work starts with a literature review of this manufacturing technique and develops a model that meets the reality it is intended to represent and has acceptable limitations. Then, experimental tests are conducted with two purposes, to characterise the compaction behaviour of fabric and to produce parts by recurring to the vacuum infusion process. Finally, the developed model accuracy is assessed by comparing its thickness predictions against the cured part thickness of the experimental tests and resourcing to blades available thickness data. The quality of the characterisation tests procedure is evaluated, the model efficiency is determined, and follow up steps for future work are suggested.
Keywords: Vacuum Infusion, Wind Turbine Blades, Thickness Prediction, Composite Materials.

1. Introduction

The Vacuum Infusion Process (VIP) is a composite manufacturing process that started to be investigated around the mid-twentieth century, but it was only around the 1990s when it gained its due recognition and asserted itself in the market. From that point, the composites' components demand grew, and new tooling capable of predicting and improving the design of the process was developed, revolutionising the traditional trial and error approach.

This is a close-mould process composed of one rigid side of the mould and another flexible, figure 1. The preform of dry fabric is laid on the rigid part of the mould and several other components. Afterwards, the mould cavity is sealed by the application of the flexible vacuum bag. This flexible tooling will allow thickness variations during the different stages of the process that are difficult to predict accurately. When the vacuum is applied, the pressure gradient will serve as the driver for the fluid to enter the cavity, flowing through the fabric' porous media and changing its compaction and permeability properties along the way. Since no additional pressure is applied to the mould, only the atmospheric pressure contributes to the pressure gradient and serves as the fluid's only driver. Heating systems are typically embedded into the rigid side of the mould to fasten the solidification of the part and reduce the duration of the process, [1].

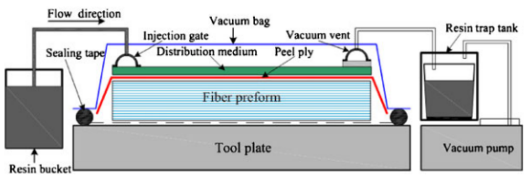


Figure 1: VI setup components, [2].

The main advantages of this process are based on the ease to change the design of the setup and adapt it for different parts. The vacuum bag application also improves the control over the infusion and allows actuation measures during the process stages. The harmless Volatile Organic Components (VOC) only are emitted before the infusion, reducing the health risks associated with the technique. On the other hand, the human skills and the quality of the consumable materials are too determinant to achieve a successful production. The setup is susceptible to air leaks challenging to repair, and the pressure differential limitations imposed by the atmospheric pressure will also contribute to the process disadvantages. One of the leading VIP drawbacks is settled on the non-uniform thickness distribution of the cured plies due to the flexibility of the vacuum bag, which may jeopardise the assembly or the application of the final component.

Balancing the previous points, it can be concluded that this process is particularly suitable for producing more extensive and more complex composite parts, such as turbine blades, boat hulls and aircraft structures. It has applications in several industries, and its continuous growth indicates that it will reach and cover even more areas. The marine, automotive, infrastructures, renewable energies and aerospace are the primary industries with more VIP applications, [1].

The VIP shares features from the Resin Transfer Moulding (RTM) and the hand layup process. The fact that it is a close-mould process, similar to the RTM, reduces the VOC emissions and the handling during the process is much cleaner and safer. The part quality and repeatability of the process are also similar for these processes. On the other hand, the flexible side of the mould allows to scale the setup and adapt it for more extensive parts, like in the open-mould hand layup process. Financially speaking, the VIP can be inserted in between the RTM and the hand layup process.

Currently, wind turbine blades are produced by the VIP and therefore are susceptible to the process advantages and disadvantages. The final blades assembly is ultimately dependent on the thickness of each part of the blade. If predictions are not accurate, projects will suffer delays in the manufacturing stage, and their costs will rise possibly until unbearable values. The ultimate goal of this work is to develop an analytical model capable of predicting the cured ply thickness of blades within the preexisting admissible error interval. For that purpose, the layup influence on the ply was defined as the main target of study.

1.1. Literature review

The VIP starts with the setup preparation. In this stage, the components are placed in the setup, and the connections are mounted. Then, the pre-filing stage takes place, and the air is extracted from the setup with the aid of the vacuum pump. After reaching full vacuum inside the mould cavity, the resin system is prepared separately and then the impregnation of the fabric by the resin fluid occurs, the denominated filling stage. After full saturation of the fabric is achieved, the post-filling stage starts and the resin is still able to flow and will tend to find an equilibrium of its pressure distribution throughout the preform. Eventually, the resin will lose its fluid properties and act first as a gel until starting the curing stage, where the resin system and the preform consolidate and form a single composite part. There are several strategic alternatives for each of these stages, which were investigated in [2–4].

The fabrics with the most recurrent applications in industry are the Non-Crimp Fabrics (NCF) and the woven fabrics. The NCFs are composed of multiple layers of unidirectional fibres stacked with the same or different orientations and stitched together. The woven fabrics include fibre bundles in their through-thickness direction to form a structural pattern that improves their properties in that direction. Their geometrical properties and their behaviour under certain load conditions were assessed in [2, 3].

During the VIP stages, the fabric will undergo thickness variation phenomena, and its impact is mainly dependent on the type of fabric and duration of the phenomena. Nesting is a measurable phenomenon that represents the layers' ability to slide between themselves and is related to the perfection of the layers' alignment. It quantifies the thickness per layer variation when dealing with thicker layups, [2]. Lubrication is also a measurable phenomenon that occurs during the instant when the fabric is being saturated. The resin acts as a lubricant and allows a better accommodation of the fibres, [5, 6]. Materials are also susceptible to time-dependent phenomena due to their viscoelastic properties, imposing variations under stable conditions over a specific period, [7].

To accurately predict and understand the VIP, it is necessary to acknowledge the compaction and the permeability behaviour of the applied fabric. It is possible to find several studies either focused on these two types of material characterisation or to use them for further study tasks. The compaction behaviour represents the response of a fabric that is subjected to a specific compaction load, [2–5, 7, 8]. The permeability behaviour represents the ability of a fluid to flow through the porous media of material under specific pressure conditions, [4, 5, 8, 9]. Some setups and several factors were already priorities of studies for both types of tests. Alongside these characterisations, vacuum infusion tests are also very traditional to occur, but their goal is more related to validating VIP predictive models, [4, 6–10].

2. Thickness prediction model

Mathematical models are tools that engineers and other professionals use to represent reality. They must be based on mathematical concepts that carry physical values and are built on governing equations. The three governing equations in VIP are the continuity equation, equation (1a), the momentum equation (Darcy's Law), equation (1b), and the stress equilibrium equation (Terzaghi's Law), equation (1c).

$$\frac{\partial}{\partial t}\int_V (\rho \cdot \phi)\, dV = -\oint_S (\rho \cdot u \cdot \hat{n} \rho \cdot u \cdot \hat{n})\, dS \quad (1a)$$

$$\vec{u} = -\frac{K}{\mu}\nabla P \rightarrow \vec{u_x} = -\frac{K}{\mu}\frac{\partial P}{\partial x} \quad (1b)$$

$$P_c = P_{atm} - P_{vac} - P_r \quad (1c)$$

The fabric's deformability is included in the model by the continuity equation, where the flow through the boundaries of a controlled volume of density ρ is related to its rates of expansion and contraction and the fluid media porosity, ϕ, [9]. The Darcy's Law represents the average volume velocity of a flow-through a porous media, $\vec{u}$, it was initially developed for hydrogeology, and in equation (1b) it is applied to a 1D flow, $\vec{u_x}$. This volume average velocity is related to the part permeability, K in [m^2], the resin viscosity, μ in [Pa s], and the pressure gradient, ∇P. Terzaghi's Law is the equation that relates the distribution of the total pressure available between the pressure supported by the fabric, P_c, and the resin, P_r, by the through-thickness direction, figure 2. This total available pressure equals to the atmospheric pressure, P_{atm}, that is constantly applied on the vacuum bag minus the vacuum pressure inside the mould, P_{vac}, which is mostly affected by the vacuum pump capacity and the quality of the setup.

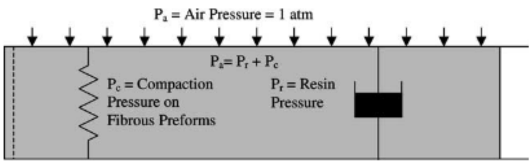


Figure 2: Pressure distribution inside the mould, [11].

One of the first authors developing a model integrating all these governing equations were Hammami and Gebart in [8]. A thorough study, [10], followed this article and significant VIP analytical steps were taken. With the Correia et al. model, developed in [9], the pressure profile was for the first time assumed to be scalable. This model was further detailed in [9], where its assumptions and manipulations were demonstrated and justified. The Correia et al. model is well accepted in the scientific community, and several developments and validations have been conducted since then. The model was applied to predict the thickness of a part during VIP in [6, 12]. It combines the governing equations and manipulates them until reaching the Ordinary Differential Equation (ODE) presented in equation (2).

$$\frac{\partial^2 P}{\partial \alpha^2} = \left(\frac{h^* \cdot \alpha - 1}{h} \cdot \frac{\partial h}{\partial P} - \frac{1}{K} \cdot \frac{\partial K}{\partial P}\right) \cdot \left(\frac{\partial P}{\partial \alpha}\right)^2 \quad (2)$$

Being P the resin pressure, h the thickness, h^* the dimensionless thickness and α the dimensionless parameter, with $\alpha = 0$ and $\alpha = 1$ representing the inlet and the flow front, respectively, regardless of time. Thickness and permeability must be related to the pressure to be included in the ODE derivatives. For that purpose, empirical formulas are applied. The Kozeny-Carman formula, equation (3a), most commonly characterises permeability. Compaction empirical formulas examples are presented in equation (3b) and equation (3c). Furthermore, thickness is converted in fibre volume fraction (FVF) by equation (3d).

$$K = k_o \cdot \frac{(1 - V_f)^3}{V_f^2} \quad (3a)$$

$$V_f = V_{f0} \cdot P_c^B \quad (3b)$$

$$V_f = a \cdot P_c^b + c \quad (3c)$$

$$h = \frac{\rho_{sup} \cdot nol}{\rho_{bulk} \cdot V_f} \quad (3d)$$

Where k_0 and V_{f_0}, B, a, b, c are the permeability and compaction empirical constants, respectively. V_f is the FVF, ρ_{bulk} and ρ_{sup} are the fibres bulk and areal density, respectively, and nol the number of layers.

This Correia et al. model was first used in this work because it suited the requirements defined for the thickness prediction. A simple *MATLAB* code was used to apply the model, and the flow was not simulated because time was not a variable. The layup design, properties, and pressure conditions were the only inputs, and thickness distribution was part of the output. Finally, if the model were validated, it would be easy to update for new materials, and its utilisation would not be difficult, making it accessible to those needing to use it.

The improvement made to this model was the inclusion of formulas capable of relating more than one fabric in a layup, combining their compaction, equation (4a), and permeability properties, equation (4b), to calculate the overall layup behaviour. k is the index for the layers in the layup, and h_T is the total laminate thickness.

$$V_f = \frac{\sum_{k=1}^{n} \rho_{sup_k} \cdot nol_k}{\sum_{k=1}^{n} \frac{\rho_{sup_k} \cdot nol_k}{V_{f_k}}} \quad (4a)$$

$$K = \frac{\sum_{k=1}^{n} K_k h_k}{h_T} \quad (4b)$$

2.1. Model applicability for blades

Framing the conditions of applying this new version of the model into the production of blades, it is understandable that it does not fit. The main reasons are detailed below:

- **Distribution Mesh -** Almost all composite materials produced by the VIP use distribution meshes in their setup in order to reduce the infusion times. Particularly to the turbine blades, their relative thickness would make it unfeasible to match product deliveries deadlines.
- **Layup Variability -** In a typical blade, the layup in the root only has a few similarities with the one on the tip. Since the structural efforts in both zones are different, the layup will vary according to its needs.
- **VIP Stages Duration -** Each blade model has its defined procedure that must be followed during the process. Nevertheless, infusions of such considerable-sized parts have several obstacles that may affect the duration of all stages, especially during the pre-filling stage. If any air leak is present, it is required to analyse the whole blade, which could take a significant time.
- **Setup Complexity -** The setup to produce a blade is very complex, and in literature, there are no similar examples. The resin inlets and outlets are not straightforward, and systems combining inlets and outlets are used. Furthermore, the fluid does not flow in a plane mould since blades have a curvature associated.

All of these production characteristics violate the principles that support the developed model. It was decided that even if validated, the model would not be appropriate to predict the thickness of a blade and would not be helpful for its production.

2.2. Model simplification for blades

Even when considering the complexity of the setup design of a blade, it is possible to find an area where some assumptions can be made to justify a simplification. At the central spanwise cross-section of a blade, it is possible to infer the following:

- **Setup Geometry -** Despite being a rough approximation, in this section, the setup can be considered plane. The curvature of the blade is estimated to start for both sides of this section in the chordwise direction.
- **Number of Layers -** Even though the layup varies significantly throughout the spanwise direction, all radius sections can be addressed separately. There are also thin layups that can be easier to assess at a first model validation.
- **Fabric Variability -** Blades are produced with several fabrics in different parts according to the structural needs. Usually, the fabric variability in this section is not complex compared to other sections, and only a few materials are combined.

Thus, it is feasible to apply the model to each layup in this central spanwise cross-section and have a thickness prediction distribution through it all. In order to run the model, there is no need to include the permeability data and iterate the ODE to find the pressure distribution profile because, at this point, pressure will be considered a constant. Thus, only an empirical formula that characterises the compaction behaviour of the material and equation (3d) are used.

Having this defined, the further steps for this work are based on conducting material characterisation tests to assess the compaction behaviour of the material, conducting infusion tests to validate the model under controlled conditions, and validating the model using cutup data provided by a third entity.

3. Experimental tests

The main reason to conduct the material characterisation experiments is based on the lack of available data of the individual compaction behaviour of the fabric applied on blades. Even though in literature similar materials were characterised, they do not have the same geometry nor properties. The infusion tests will be conducted to validate the model in a more controlled environment, involving a simple setup without complex geometries, avoiding layups with non characterised fabrics and using the same number of layers as the ones characterised. The main distinction between both tests is that only air is used as test fluid for characterisation tests, whereas resin is also applied for the infusion tests.

3.1. Material characterisation tests

Even though several studies conducted tests similar to the ones presented here, there is no standard procedure or norms to follow during these tests. Furthermore, the author had no previous experience related to the VIP or other composites laboratory equipment. Thus, some adjustments and iterations occurred after the first round of characterisation tests that will not be fully described here. These tests were repeated because the standard deviation did not match expectations, and several factors introduced errors in the procedure. The ones with more relevance were table tilting by the vacuum pump performance, presser feet deformation due to its production technique, calculus of the areal density of each stacking and methodology to measure the initial thickness of each preform. After conducting this error analysis, the experimental procedure was improved, and tests were repeated.

The Design of Experiment (DoE) consists of a structured plan for the tests, namely to define the variables that will be assessed, the factors, and their range, the levels. Here, only one fabric was characterised, the unidirectional glass fibre with twelve hundred grams per square meter, UD 1200 gsm, and the only factor assessed was the number of layers, $nol = 4, 8, 16, 32$. Each test was repeated three times in order to ensure good repeatability. The tests order was randomised to avoid bias in the data.

The setup for this round of tests counted using an acrylic table, serving as the mould, the fabric, the consumable materials, the vacuum pump, the resin trap and the sensors framework. The consumable materials include tacky tape, universal tape, resin spirals, resin hoses and the vacuum bag. The sensors framework consisted of metallic bars connected to magnetic equipment to fix their positions and supported the micrometres responsible for measuring thickness. Figure 3 is a representation of the setup. Even though it displayed two micrometres, only the digital one on the left was used for these tests.

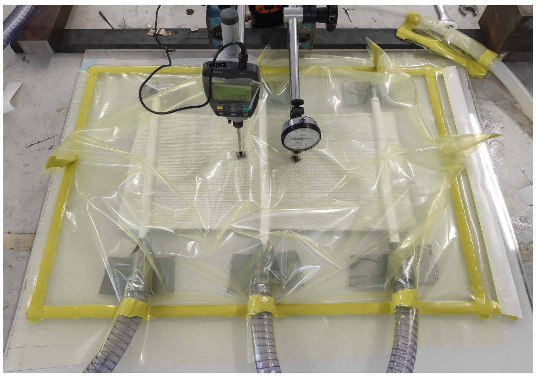
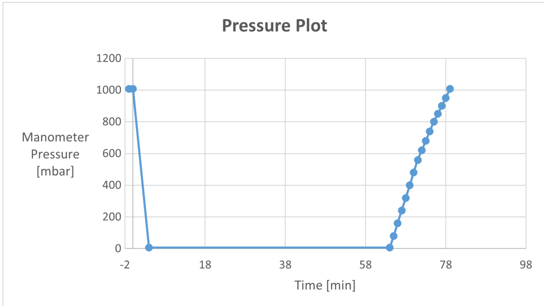


Figure 3: Setup for material characterisation tests.

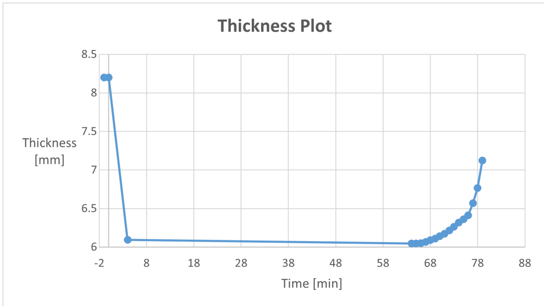
The resin hoses on both ends of the preform are connected to the vacuum pump, serving as channels to extract air. The central hose is connected to a manometer to measure pressure close to the thickness measuring point. This strategy makes the pressure distribution in the preform more homogeneous.

The characterisation tests could occur with the fabric in its dry or wet state. It was decided to discard resin inclusion to simplify the procedure and minimise health hazards. It was found literature supporting the characterisation of the material in this state, [2]. Another great advantage of this option is avoiding the need to replace all resin hoses due to resin contamination after each test, reducing the duration of each test.

The pressure plot applied during these tests and the correspondent thickness are presented in figure 4. Figure 4(a) is the generic plot applied to all tests, while figure 4(b) is the thickness recorded from a specific test.



(a) Revised pressure plot.



(b) Thickness plot for $nol = 8$ test.

Figure 4: Plots for characterisation tests.

The VIP stages studied here are the settling and the unloading, corresponding to the second and the third parts of the plots. During the settling, the pressure is kept constant for over sixty minutes to record the slight thickness variations by the viscoelastic effect of the fabric. Then, using a ball valve to allow air reentering the setup cavity, the manometer pressure will be incremented step by step until reaching the atmospheric pressure, after fifteen increments. The preform will be rapidly compacted in compaction pressure by turning the vacuum pump on until the vacuum pressure. Then it will be kept constant and finally will be consecutively decreasing, allowing thickness to expand.

Equation (5) was applied to all tests to assess the thickness variation, Δh_{set}, over the sixty minutes. $h_{set_{initial}}$ and $h_{set_{final}}$ are the thickness when settling starts and ends, respectively.

$$\Delta h_{set} = \frac{h_{set_{initial}} - h_{set_{final}}}{h_{set_{initial}}} \cdot 100 \qquad (5)$$

The results for all tests are clustered by the number of layers, and only their average and standard deviations (SD) are presented in table 1. These thickness variations were plotted against the number of layers, figure 5, and a power function was fitted to the curve, equation (6). This analysis can infer how much settling will occur for a preform of any number of layers if subjected to a total vacuum for sixty minutes.

Table 1: Thickness variation during settling clustered by nol.

nol		4	8	16	32
Δh_{set} [%]	Average	0.684	0.397	0.269	0.171
	SD	0.170	0.052	0.003	0.011

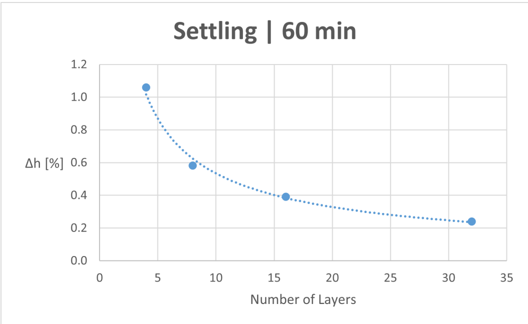


Figure 5: Thickness variation during settling stage.

$$\Delta h_{set} = 2.6896 \cdot nol^{0.702} \tag{6}$$

The thickness was measured in each of the fifteen increments of pressure during the unloading stage, corresponding to the third part of the plot in figure 4(b). Through the application of equation (3d), it is possible to convert that part of the plot into compaction pressure against FVF. From here, the least square method (LSM) can fit the curve into a linear regression by applying logarithmic scales. Thus, each linear regression will allow the calculation of the pair of empirical constants describing the compaction behaviour of the fabric.

These constants were used to plot each test' empirical curves to cluster them in terms of the number of layers. The average curves per cluster are represented in figure 6. For the point of highest compaction plotted, $P_c = 950\,\text{mbar}$, the SD was reduced by 46.19% by passing from four to eight layers, 54.24% by passing from eight to sixteen layers and 85.95% by passing from sixteen to thirty-two layers. This trend supports the statement that standard deviation should follow a decreasing trend with the increment of the number of layers and conclude that the new tests procedure significantly improved the results of the tests.

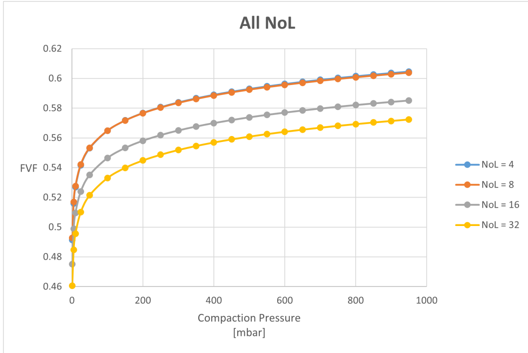


Figure 6: Average empirical curves.

The evolution of the empirical curves with the increasing number of layers supports the fact that thicker layups have their nesting ability reduced. Thus, the FVF will be lower for thicker than for thinner layups for the same compaction pressure. The following points are presented to validate this data:

- **Literature Review -** In subsection 1.1, some articles were cited which defended that nesting would improve, not be influenced and would decrease with the increment of the number of layers. Therefore, any possible trend was expected for this analysis.
- **Nesting Definition -** Nesting is directly related to the alignment perfection of all layers in the layup. This alignment is more difficult to achieve for a higher number of layers. Thus, it is expected to have a worse nesting ability for thicker layups. If measures were taken to ensure a proper alignment, it would be expected to improve nesting by incrementing the number of layers.
- **Blades Production -** Very thick layups are stacked without a rigorous methodology. Due to the blade complex geometry and the concentration of layers present, it is challenging to ensure proper alignment of layers and tolerances are applied. This mismanaged alignment is typical when stacking layups for blades and can be consequently considered representative.

The plot in figure 6 has the empirical curves for four and eight layers overlapped. This overlapping can be accepted due to their relatively high standard deviations, which impose a wider interval for the curves positioning. The empirical constants for the average curves per cluster are presented in table 2.

3.2. Infusion tests

The goal of conducting these tests is to have cured ply thickness measurements to validate the devel-

Table 2: Empirical constants per *nol*.

nol	4	8	16	32
V_{f_0}	0.4275	0.4299	0.4131	0.3982
B	0.0302	0.0296	0.0304	0.0317

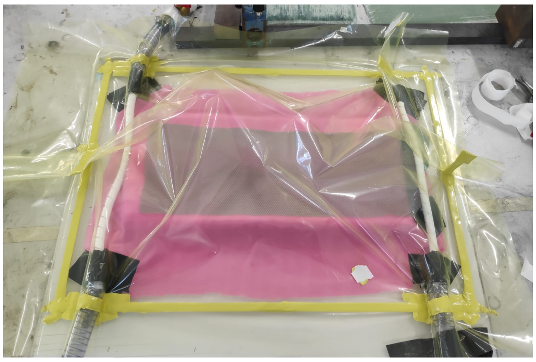


Figure 7: Setup for infusion tests.

oped model. Similar conditions must be shared between the characterisation and the infusion tests to reduce the number of variables introducing error. Another objective for these tests is to resemble as further as possible the process conditions used for the production of the blades.

The DoE for the characterisation tests conditioned the one for the infusion tests. Thus, the factors and the levels used in the first DoE served as the limit for the second DoE development. Due to time restrictions imposed on the project, only some tests occurred. The fabric used was the same, the UD 1200 *gsm*, and the number of layers was again the only factor, $nol = 16$, and the number of repetitions used was the same, $nor = 3$. At first, one trial infusion was conducted with $nol = 8$. Since this infusion followed the same procedure as the other ones and the test was considered a success, its thickness values will be considered for the model validation.

The setup used for the infusion tests is similar to the one presented in figure 3. More concerns are raised regarding setup design because the resin will flow inside the cavity, which leads to the inclusion of the following materials. The release agent is a component used inside the tacky tape limits, and it is applied to the mould to ease the removal of the part during the demolding stage. The peel ply has a similar effect but eases the removal of the consumable materials from the part itself. The distribution mesh can be considered an accelerator of the flow, its relatively high permeability allows the resin to flow faster through its porous media, shortening the filling times of these tests. The setup is illustrated in figure 7.

Even though this figure does not have the sensors framework placed, they were used to record thickness data during the tests. Nevertheless, their utility during the tests was not as significant as in the previous tests because the goal for the infusion tests is to measure the cured ply thickness of the parts. For that purpose, the measurements are only vital after the demolding stage of the process.

One difference in this setup is related to the number of inlets and outlets. Here, one channel is used for the resin to enter the setup, on the right of figure 7 and the other channel, on the left of the figure, has two different purposes. One is to extract air and later resin, and the other is for pressure measurements. The resin hoses are connected to the setup in three different zones, and all of them are associated with a determined ball valve. These ball valves are helpful for the experimental procedure. The outlet and sensor hoses share the same resin spiral to reduce the number of consumable materials per test.

Infusion tests also do not have stipulated guidelines for their procedure. Nonetheless, they are more recurrent, and there is a solid common practice within the scientific community and corporate application. The experimental procedure used for these tests is based on the common practice framed in the wind energy industry production reality.

After the setup is prepared, the vacuum pump is turned on, and the air is extracted from the cavity. Then, for infusion to occur, full vacuum conditions must be achieved to ensure that air leaks that may jeopardise the test are not present. For that purpose, a drop test is conducted and only if valid the procedure may follow. Afterwards, the resin system must be prepared according to the weight of the preform. The epoxy and the hardener were mixed, and the result was left for degassing for ten minutes. Then, the resin deposit was connected to the setup, and the fluid impregnated the fabric by using the pressure differential as the driver. A few moments after the fluid reached the resin outlet hose, its clamp was closed, and a few moments later, the inlet hose was also closed. The setup cavity reached a total saturated condition, and the part entered the post-filling stage. Without any further action, curing occurred, and then the part was demolded.

During the second infusion test, with sixteen layers, a problem was raised in the drop test, and by negligence, the setup was wrongly thought prepared for infusion. The analysis discarded the cured part from this test due to its high content of the air.

Regarding the remaining three cured parts, nine measurements were taken in the areas represented in figure 8. The three thickness values in the "Left" column were thought to be sufficiently disparate from the other two columns due to the high resin concentration near the outlet port. Thus, the averaged values from the remaining six measurements were considered. These measurements are presented in table 3.

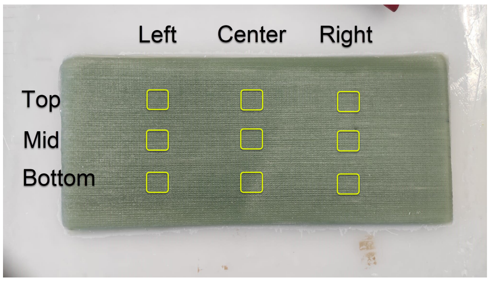


Figure 8: Areas for cured ply thickness measurements.

Table 3: Average thickness measurements.

Infusion	I1	I3	I4
nol	8	16	16
$h_{average}$ [mm]	7.115	14.154	14.136

4. Model validation

The validation of the developed model will be based on two different components. The infusion tests conducted will serve as an initial validation. Later, blades data for a specific layup will be used to assess the accuracy of the predictions.

4.1. Infusion tests

To run the model, it is necessary to know the layup and the pressure conditions. Since the layup was already presented in the subsection 3.2, it is only needed to discuss the pressure conditions. After the filling stage, the preform will be saturated with fluid resin that eventually will cure. When curing starts and until the demolding stage, the available pressure inside the setup will be supported by the combination of fabric and the resin as one part. Thus, the atmospheric pressure minus the vacuum pressure achieved in each test has to be the pressure used for predicting thicknesses. These pressures are presented in table 4.

The strategy used for the empirical constants was settled on using the empirical pair correspondent to the number of layers in the infused layup, $h_{model_{8,16}}$, and on using the empirical pair for thirty-two layers, $h_{model_{32}}$. This alternative was chosen to assess the utilisation of the characterisation with the lowest deviation to understand if it improves the predictions. The predicted thicknesses for the three infusions are presented in table 5.

The percentage relative error for each model validation was calculated according to equation (7) and are presented in table 6

$$\epsilon_{model} = \frac{|h_{model} - h_{average}|}{h_{average}} \cdot 100 \qquad (7)$$

Table 4: Pressure conditions in all infusion tests.

Infusion	I1	I3	I4
nol	8	16	16
P_{atm} [mbar]	1007.9	1006.7	1008.2
P_{vac} [mbar]	25.23	19.01	16.32
$P_{available}$ [mbar]	982.7	987.7	991.9

Table 5: Thickness predictions for all infusion tests.

Infusion	I1	I3	I4
nol	8	16	16
$h_{model_{8,16}}$ [mm]	6.256	12.900	12.898
$h_{model_{32}}$ [mm]	6.593	13.184	13.182

Table 6: Predictions error.

Infusion	I1	I3	I4
nol	8	16	16
$\epsilon_{model_{8,16}}$ [%]	12.07	8.86	8.76
$\epsilon_{model_{32}}$ [%]	7.33	6.86	6.75

It is clear that using the empirical data for thirty-two layers significantly improves the prediction. Furthermore, the prediction error for thinner plies is higher than for thicker plies. This error can be related and associated with the standard deviations calculated in the material characterisation data. Thinner layups imply more variability in the handling and may result in a broader range of cured thickness. The assessment of only one infused part with eight layers limits this analysis severely and does not support this conclusion, regardless of being aligned with previous evidence from other tests.

4.2. Cutup data

The cutup data consists of the thickness data collection of mock-ups produced with the same conditions as the turbine blades. These parts are cut at specific points, and thickness is measured at different zones of the section. Since blades have complex setups, procedures and layups associated with their production, only a specific part of the main carbon path was selected for this study.

These sections share their layup composition, allowing to compare the model prediction with different measures. The layup scheme is not illustrated here. One vital point to underline is that several fabrics are part of this layup, and only one of them was studied in compaction behaviour. Thus, the empirical characterisation of the remaining fabrics will be researched and used from the literature, introducing a new error factor in the prediction model. The thickness of the three materials on the bottom of the stacking (SPL, Surface Veil and Gel Coat) will be considered in the model according to the industry traditional predictions because their empirical constants were not found in the literature. The remaining two materials (Biax and Triax) have their constants presented in table 7. The characterisation of the Biax and the Triax materials were conducted in [5] and [2], respectively. The Biax data was fitted into equation (3b) while the Triax data was fitted into equation (3c).

The available vacuum pressure for all blades productions is estimated to be around $P_{available} = 950\,\text{mbar}$. Similar to what occurred for the infusion tests, the empirical data calculated in the experimental tests will be used for the respective and the remaining number of layers clusters. The layup has eight layers of the characterised material, but the pair of empirical constants of sixteen and thirty-two layers will also be used.

Thickness predictions are presented in table 8. These predictions will be compared to thickness measurements from eight sections. The cutup data for these sections is presented in table 9. Overall, the prediction with the empirical data for thirty-two layers is better. Thus, only its prediction error calculated with equation (7) will be presented in table 10.

Regardless of the indication provided by this error analysis, it is furthermore needed to analyse the thickness variation between predictions and actual values. The maximum thickness variation is 0.78 mm, which corresponds to an acceptable error for the assembly of the blade. Nevertheless, since this layup represents a thinner part, it is relatively easier to be included in the admissible interval. Further validations for thicker parts of the blade should be conducted.

To understand the improvement from using the empirical data gathered in the experimental tests for the glass fabric, empirical data found on literature for similar fabrics was used to run the model. In [2], an unidirectional glass fiber with identical areal density was characterised, using its empirical constants results in a thickness prediction of $h_{model} = 10.60\,\text{mm}$. This thickness prediction was compared to the cutup sections evaluated in this thesis, and a maximum and minimum associated error of $\epsilon_{max} = 9.22\,\%$ and $\epsilon_{min} = 2.06\,\%$ were calculated, respectively. This analysis alone does not conclude that the characterisation of the fabric in the experimental tests resulted in a more accurate prediction but sustains a considerable motivation to pursue the characterisation of the remaining fabrics.

Table 7: Empirical constants data of Biax and Triax.

Biax		Triax		
V_{f_0}	B	a	b	c
0.3621	0.0317	32.88	0.267	42.13

Table 8: Layup thickness predictions.

h_{model_8} [mm]	$h_{model_{16}}$ [mm]	$h_{model_{32}}$ [mm]
10.56	10.75	10.90

Table 9: Cutup data thickness measurements.

h_1 [mm]	11.33	h_5 [mm]	11.00
h_2 [mm]	11.68	h_6 [mm]	11.00
h_3 [mm]	11.13	h_7 [mm]	11.00
h_4 [mm]	10.82	h_8 [mm]	11.00

Table 10: Thickness predictions error.

ϵ_1 [%]	3.80	ϵ_{5-8} [%]	0.91
ϵ_2 [%]	6.65		
ϵ_3 [%]	2.10		
ϵ_4 [%]	0.71		

5. Conclusions

The degree of complexity of a blades geometry and the usage of distribution mesh are determinant factors to complicate the validation of the most recurrent models to predict the pressure distribution field. It is recommended to use a more simple approach based on academic models coupled with an intense validation against experimental results to develop a thickness prediction model for the infusion of turbine blades.

In the material characterisation tests, increasing the number of layers reduced the standard deviation, improving the tests' repeatability. Furthermore, this increment also results in a higher thickness per layer in the layup, lowering the final FVF value for thicker laminates. This trend is believed to result from a worst layers alignment in the stacking procedure, culminating in a worse nesting ability of the overall layup.

Using the empirical data for thirty-two layers provided the most accurate thickness predictions. This accuracy concludes that the tests with the lowest deviations, the more exact, described the compaction behaviour of the fabric with precision. This finding also supports the alternative to remove thinner layups from the characterisation tests DoE only to use thicker layups.

The model validation against specific cutup data was very accurate, and considerably low error values were calculated. The differences between the predictions and the cutup data were inside the admissible thickness interval that avoided clashes in the blade assembly. The layup that was assessed integrated different fabrics that were either characterised by literature empirical data or by the industry data, which introduced a new degree of uncertainty to the results.

Using the empirical data gathered from the experimental tests resulted in a predictions improvement. Literature empirical data of a very similar fabric was used in the model, and the predictions error increased. This verification supports the characterisation of the remaining fabrics used in the layup to understand their influence on the validations.

For future work, it is recommended to characterise the fabric in its wet state to increase the degree of resemblance to the infusion tests. More repetitions per test are imperative to reach a statistically relevant analysis. The nesting effect should be included in the DoE to have its assessment. Including pressure transducers in the mould should also be a priority to understand the pressure gradient in the through-thickness direction, easing the analysis of thicker layups.

Regarding the validations, only a particular section of the blade was analysed. To accurately assess this model value, it is mandatory to have it validated for all blade sections. Current methodologies applied in the industry must also be fully acknowledged, and if possible, incorporated in a new version of the model.

Acknowledgements
The author would like to thank *Vestas* for the knowledge sharing and resources allocated to the project, and *Instituto Superior Técnico* for the laboratory access.

References

[1] S. G. Advani and K. T. Hsiao. *Manufacturing techniques for polymer matrix composites (PMCs)*. Cambridge: Woodhead Publishing, 2012.

[2] Jinshui Yang, Jiayu Xiao, Jingcheng Zeng, Dazhi Jiang, and Chaoyi Peng. Compaction behavior and part thickness variation in vacuum infusion molding process. *Applied composite materials*, 19(3):443–458, 2012.

[3] Samuli Korkiakoski, Mikko Haavisto, Mohammad Rostami Barouei, and Olli Saarela. Experimental compaction characterization of unidirectional stitched noncrimp fabrics in the vacuum infusion process. *Polymer Composites*, 37(9):2692–2704, 2016.

[4] Baris Caglar, Mert Hancioglu, and E Murat Sozer. Monitoring and modeling of part thickness evolution in vacuum infusion process. *Journal of Composite Materials*, 55(8):1053–1072, 2021.

[5] M Akif Yalcinkaya, Baris Caglar, and E Murat Sozer. Effect of permeability characterization at different boundary and flow conditions on vacuum infusion process modeling. *Journal of Reinforced Plastics and Composites*, 36(7):491–504, 2017.

[6] Bekir Yenilmez and E Murat Sozer. Compaction of e-glass fabric preforms in the vacuum infusion process:(a) use of characterization database in a model and (b) experiments. *Journal of composite materials*, 47(16):1959–1975, 2013.

[7] Bekir Yenilmez, Baris Caglar, and E Murat Sozer. Viscoelastic modeling of fiber preform compaction in vacuum infusion process. *Journal of Composite Materials*, 51(30):4189–4203, 2017.

[8] A Hammami and BR Gebart. Analysis of the vacuum infusion molding process. *Polymer composites*, 21(1):28–40, 2000.

[9] NC Correia, F Robitaille, AC Long, CD Rudd, P Šimáček, and SG Advani. Analysis of the vacuum infusion moulding process: I. analytical formulation. *Composites Part A: Applied Science and Manufacturing*, 36(12):1645–1656, 2005.

[10] NC Correia, F Robitaille, AC Long, CD Rudd, P Šimáček, and Suresh G Advani. Use of resin transfer molding simulation to predict flow, saturation, and compaction in the vartm process. *J. Fluids Eng.*, 126(2):210–215, 2004.

[11] Jeffrey A Acheson, Pavel Šimáček, and Suresh G Advani. The implications of fiber compaction and saturation on fully coupled vartm simulation. *Composites Part A: Applied Science and Manufacturing*, 35(2):159–169, 2004.

[12] Bekir Yenilmez, Murat Senan, and E Murat Sozer. Variation of part thickness and compaction pressure in vacuum infusion process. *Composites Science and Technology*, 69(11-12):1710–1719, 2009.