The Prediction of Multi-scale Voids and Their Mechanical Effect on Thick Composite Structures Manufactured by RTM

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# The Prediction of Multi-scale Voids and Their Mechanical Effect on Thick Composite Structures Manufactured by RTM

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### Abstract

Thick composite laminates can be used in aerospace and automotive industry replacing metals for weight saving. Increasing the thickness can bring more defects, like voids. This master thesis focuses on the multi-scale voids prediction and their mechanical effect simulation of thick composite laminates manufacturing by Resin Transfer Molding (RTM). It could be potentially used in safe design of thick composite components. The main objective of the thesis work is to analyze the effect of multi-scale voids caused by the filling process on mechanical properties of thick composite laminates.

First is using PAM-RTM to simulate the locations of voids and their percentage. Then, the material properties of each Microstructural Volume Element (MVE) with different micro and macro voids are evaluated by Digimat at micro and meso scales. After that, the macro-scale material properties of the thick laminates are simulated in ABAQUS. The simulation processes are verified by using the parameters from the literature and then comparing with the published results.

The simulation from PAM-RTM indicates the average void percentage of the whole laminate reduces with the increasing injection pressure or permeabilities. The total void volume increases with an increasing laminate thickness but the average void volume does not change with the changing thickness. The result of this thesis suggests that the effect of multi-scale voids on material properties (i.e., Young's modulus, Poisson's ratio, and Shear modulus) does not change due to an increasing thickness. The writing presents the actions taken in order to achieve the objective of the research successfully.

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# Nomenclature

### List of Acronyms

FRPCs	Fibre-Reinforced-Plastic Composites
LCM	Liquid Composite Molding
RTM	Resin Transfer Molding
ILSS	InterLaminar Shear Strength
FE	Finite Element
Da	Damkohler Number
MVE	Microstructural Volume Element
FECV	Finite Element/Control Volume
VOF	Volume of Fluid
LIMS	Liquid Injection Molding Simulation
VARI	Vacuum Assisted Resin Infusion
C-RTM	Compression RTM
2D	Two-Dimensional
1D	One-Dimensional
3D	Three-Dimensional

### List of Symbols

Viscosity
Pressure gradients
Resin surface tension
Permeability
Pressure gradient
Advancing contact angle
Fluid front velocity
Modified capillary number
Diameter of a single fibre filament in meter
Form factor
Form factors between the yarns
Form factors in the yarns
Flow front locations between the yarns
Single tow length
Flow front locations in the yarns
Capillary pressure within yarns
Volume average flow rate
Void content
Fibre volume per yarn
Void percentage of macro voids
Void percentage of micro voids
Tow volume

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# Chapter 1

## Introduction

### 1.1 Background and Motivation

Fibre-Reinforced-Plastic Composites (FRPCs) have received considerable attention in bridgebuilding, ship-building, automotive and aircraft industry, mainly due to their higher strength and stiffness and lower weight compared to most metals. For future weight and fuel saving, 'thick' structural components (e.g., the landing gear, submarine hulls, wind turbine blades) are required to use FRPCs instead of metallic materials.

Autoclave with prepregs is one of fabrication techniques for high performance FPRCs structures. However, the cost per kilogram of prepregs (raw material and transport) and autoclave process is higher than that of metallic materials and corresponding processes [14]. Besides, although it is possible to fabricate more complex-section components by the autoclave process, additional operations are needed to give the final shape. Furthermore, the low productivity (10-100 parts/year) of the autoclave process limits its usage [15]. Consequently, cost-effective LCM with a medium productivity (100-10<sup>5</sup> parts/year) [15] is what industries are looking for.

RTM, one of Liquid Composite Molding (LCM) techniques, includes four steps shown in Figure 1.1. First, dry fibrous plies are laid up in designed orientation in a shaped mold cavity. The resin with the curing aging is then injected into the closed mold cavity until it fully impregnates the dry fabric. After curing and cooling, a component is eventually obtained after demolding from the cavity. However, apart from the cost and time saving, a qualified FRPC laminates should have a comparable performance and high quality [16]:

- The percentage of voids or porosities is smaller than an allowable value (e.g., 2% [17]);
- Most or all of the resin is cured;
- Fibre orientations do not change because of manufacturing processes;
- Inter-facial bonding between the resin and fibres is strong enough as intended, which can transfer load between the resin and fibres;



Figure 1.1: Resin Transfer Molding (RTM) manufacturing steps [1].

Based on the Weibull theory [18], one of the statistical **Weakest Link Theories** of composites, materials are formed by many small elements and the failure of materials would occur when any one of these elements fails. For FRPCs, the statistical strength of laminates is dependent on the 'weakest elements' in the laminate, where the qualities of these elements are not strong enough. These 'weakest elements' are the non-avoidable defects (e.g., dry spots, residual stress, waviness) caused by various factors in design and manufacturing processes. As a result of these unavoidable defects, the number of the 'weakest elements' would rise with increasing elements [19, 20]. Hence, with a growing thickness, these rising defects and their effect should not be ignored when using RTM and other LCM manufacturing techniques.

In the filling process, due to inappropriate injection strategies, multi-scale voids (i.e., micro voids and macro voids) and dry spots can occur especially with increasing thickness. Although related injection parameters can be optimized [21], voids can only be minimized instead of being eliminated. This is mainly by cause of the non-homogeneous resin flow during the filling process.

As a result of void defects, some material properties are affected. Bowles [22] used Hercules AS/PMR-15 composite to analyze the void effect on the InterLaminar Shear Strength (ILSS), which experienced a decline when the void volume increases. Liu [23] used T700/TDE85 carbon fibre reinforced epoxy prepreg to prove that both the strengths and moduli decrease with the increasing void content. Olivier and Cottu [2] deduced an experimental method to show the longitudinal stiffness was not significantly affected by changes in the void. However, the transverse stiffness was significantly affected, shown in Figure 1.2. They also demonstrated that even if two laminates have the same void content, their respective response to an identical mechanical loading can be very different. This is mainly because of the different void sizes and locations. It is highly recommended to take the void sizes and locations through the thickness into account when predicting mechanical properties. Since the void effect could lead to mechanical softening, early failure, or part rejection [24], it is necessary to include that when analyzing the mechanical behaviours of the final parts.



**Figure 1.2:** Longitudinal tensile modulus  $(E_l)$  and transverse tensile modulus  $(E_t)$  variations as a function of void content [2].

### 1.2 Research Objectives and Procedures

The main objective of this research is formulated as the following:

"Analyze the mechanical effect of multi-scale voids on thick composite laminates manufactured by RTM"

Toward this end, the following steps are then to be taken:

- **S1:** Study voids in thick composites due to manufacturing processes, and familiarize with off the shelf software to simulate the RTM filling process;
- **S2:** Simulate the RTM filling process and predict the locations and sizes of multi-scale voids of thick composite laminates based on the manufacturing parameters from literature and material data sheets;
- **S3:** Build a repeatable, modifiable model with varied locations and sizes of voids in ABAQUS, which can be applied to do variable mechanical simulations;
- **S4:** Calculate the stiffness of thick laminates, based on the Finite Element (FE) model, in the presence of voids.

### 1.3 Thesis Layout

Chapter 2 is the literature review including the definition of 'thick' composites, the formulation of multi-scale voids, the state-of-art RTM simulation and mechanical analysis softwares. The overview of the methodology of this research is presented at the end of the Chapter 2. The simulation part of this research is described in Chapter 3, which includes the filling process simulation and the void effect simulation. Chapter 4 will focus on the results from the

simulation. A validation for verifying the practicability of this simulation processes will be presented at the end of Chapter 4. Conclusions and recommendations are given in Chapter 5.

## Chapter 2

### Literature review

This chapter introduces the fundamental of this research, which aims to further clarify the research objective. The definition of 'thick' composite laminates and the formulation of voids due to the filling process are presented in Section 2.1, and Section 2.2. Section 2.3 focuses on some mathematical models and experimental equations related with the void percentage. The effect of voids on mechanical properties would also be included in Section 2.3. Following in Section 2.4, the state-of-the-art commercial softwares of the LCM and the Finite Element (FE) mechanical simulation softwares are summarized. Key points of literature study are listed in Section 2.5. At the end of this chapter, a practicable methodology for this research is proposed.

More defects (e.g., residual stresses caused by matrix shrinkage and the fibre misalignment) caused during the manufacturing processes are shown in Figure 2.1. Considering the time limitation, only the void defect would be included in the final FE model in this research. The possible methodologies to embed more RTM manufacturing defects are given in Appendix A (residual stresses) and Appendix B (the fibre misalignment).

### 2.1 Definition of Thick Laminate

This research focuses on 'thick' composite laminates because of their benefits mentioned in Section 1.1. However, unlike metal and alloys (in ASTM B393, DIN 1622, and JIS G3115), there is no strict dimension definition of 'thick' composites.

In [25–27], the dimensionless Damkohler Number (Da) is used to identify 'thick' behavior, which relates the chemical reaction timescale to the transport phenomena rate [28]. The number is used to describe the fluids flow and the mass transfer outside the reactor. For composites, the equation is written as below:

$$Da = \frac{heat \ generated \ due \ to \ the \ polymerisation \ reaction}{heat \ conducted \ away \ from \ the \ reaction \ area}$$
(2.1)

Resin does not have a good heat conductivity like carbon fibres. Because of the slow rate of the resin heat transfer, the increasing thickness always leads to unfavorable temperature



Figure 2.1: Resin transfer molding (RTM) manufacturing defects.

overshoots during the curing process. When Da is larger than unity, the generated heat by the chemical reaction during the curing process cannot be easily conducted to the area which is far away from the polymerisation reaction area, contributing to a local temperature overshoot [25]. This composite part is called 'thick' laminate.

Li et al. [29] proposed for a thick part with 40mm to find the optimal temperature and pressure for composite laminates. Johannes [26] used thick parts in the order of 60 to 100mm to evaluate the process-induced strains during the RTM curing process. In this research, the thickness of thick laminates is limited between 20 to 50mm due to the limitation of the experiment mould dimensions.

### 2.2 Void Formulation

RTM is an efficient composite manufacturing method to impregnate the dry fabric with the liquid resin. A dry fabric involves interlacing a set of long yarns with a set of crossing yarns in different patterns, like plain weave and twill weave. A yarn includes thousands of filaments (i.e., tows or bundles). A fabric is usually considered as a porous medium in LCM. The length scales of the pores of the porous medium are highly heterogeneous in the micro scale (in fibre tows) and the meso scale (between fibre tows), respectively. Although the limitation between these two scales is not clear, the diameters of voids in meso scale are usually considered to be larger than 0.1mm, which is generally two orders of magnitude greater than these in micro scale [24]. Therefore, the resin flow through the dry fabric is normally regarded as a multi-scale problem shown in Table 2.1. Consequently, the resin flow is non-uniform and can create multi-scale voids.

	Observation scale	Size of computational domain	Flow characteristics	Medium
(	Macro scale	$>0.1 \mathrm{m}$	Darcy's flow	Porous medium
R	Meso scale	1 - 10 mm	Stokes' flow	Open gap
1-10 mm			Darcy's flow with capillary pressure at the resin-air interface	Porous medium
.1m 10μm- 1mm	Micro scale	10um to 1mm	Stokes' flow with surface tension at the resin-air interface	Solid filaments and tiny pore

Table 2.1: Different scales in a fabric and corresponding flow characteristics [8].

#### • Macro scale

At the macro scale, where the fabric can be observed by the naked eye, the fabric is usually regarded as a porous medium. At this scale, Darcy's law shown in Equation 2.2 is generally applied.

$$\langle v \rangle = \frac{\kappa}{\eta} . \nabla p$$
 (2.2)

where v is the volume average flow rate [30].  $\nabla p$  is the pressure gradient, which is applied by the injection pressure.  $\eta$  is the viscosity of the resin, a temperature and time related material property. It is independently considered in Darcy's law. For fast filling, a low viscosity is required during the RTM infusing process, which needs a high temperature. However, filling at a high temperature for a long time is not preferred because it would solidify the resin before fully impregnating the dry fabric and leaving dry spots.

 $\kappa$  is the permeability, a key parameter in the RTM process, which exhibits the degree of difficulty of the resin flow in the dry fabric.  $\kappa 1$  and  $\kappa 2$  are vertical in-plane permeabilities.  $\kappa 3$  is the permeability through the thickness. In many cases, permeabilities in these three directions are anisotropic. The values are affected by the fibre volume. In plain weave,  $\kappa 1$  and  $\kappa 2$  are similar and larger than  $\kappa 3$ , shown in Figure 2.2. All the permeabilities reduce when the fibre volume fraction increases. At the macro scale, low efficient permeabilities in different directions could be obtained by experiments [31]. To achieve a higher accuracy, Verleye et al., combining the microscopical Brinkman equation and the mesoscopic Stokes equation, built a dual-scale solver for the prediction of the permeability [32–34]. Compared to the permeability of the resin in the yarn direction, the resin permeability along the thickness is much smaller (i.e., 1 or 2 orders of magnitude) [3]. When the aspect ratios of specimens are smaller (i.e., thicker laminates), the larger permeability in the yarn direction allows the flowing resin to go through the fabric faster and go back after touching the boundary [4]. This process easily leads to a dry spot, also called the race-track effect, shown in Figure 2.3.



Figure 2.2: In-plane and through-thickness permeabilities of the carbon fabric [3].



Figure 2.3: Sketch map of the race-track effect (backflow) [4].

Accordingly, Darcy's law at the macro scale should be used to carefully design the mould and optimize the filling process for avoiding dry spots.

• Meso scale

At the meso scale, yarns are woven into a fabric. Between the yarns, there is an open gap, which can be considered as a macro pore. For the open gap, viscous force is dominant and the flow rate is represented by Stokes equation. Darcy's law is used to consider the capillary pressure at the interface between the resin and the air in yarns.

At this scale, if the flow rate in yarns is faster than that between yarns, the final composite laminates would have some macro voids, shown in Figure 2.4-(b) and (d). A MVE is usually used at this scale to preform permeability evaluation and understand tow impregnation physics [8].

• Micro scale

In yarns, there are some tiny pores at the micro scale among individual fibre filaments. The surface tension effect, which is negligible in meso scale, is significant at the micro



Figure 2.4: Void formation in and between fibre tows [5].

scale [24]. At this scale, if the flow rate in yarns is lower than that between yarns, the final composite laminates would have some micro voids, shown in Figure 2.4-(a) and (c).

As a result, RTM manufacturing can be summarized in three scales, macro-, meso-, and micro scale. At each scale, there are corresponding voids (i.e., dry spots, macro voids, and micro voids). As dry spots could be avoided by using proper injection strategies, this research mainly focuses on macro- and micro voids in meso- and micro scales, show in Table 2.2.

Table 2.2: Multi-scale MVE with corresponding voids.

MVE scale	macro scale	meso scale	micro scale
voids	dry spots	macro voids	micro voids

### 2.3 Void Content

A master curve of the modified capillary number for the fabric is normally applied to analyze the void content in meso- and micro scale. Many researchers [5–7, 19, 20, 35] have reported the void percentage of specific fabrics as a function of the modified capillary number  $(C_a^*)$ . This number is determined by Equation 2.3 and is dependent on the resin type.

$$C_a^* = \frac{\eta \upsilon}{\gamma \cdot \cos\theta} \tag{2.3}$$

The modified capillary number is a non-dimensionalized parameter, where  $\eta$ , v,  $\gamma$ , and  $\theta$  are the viscosity, fluid front velocity, the resin surface tension, and the advancing contact angle. The void content as a function of  $C_a^*$  is shown in Figure 2.5. If the modified capillary number is small, the flow rate between the yarns is slow. As a result, some macro voids are generated

in the channel region observed at the meso scale [5]. On the contrary, when the capillary number is large, micro voids are entrapped inside yarns.

All the results of specimens with various thickness (e.g., 3mm [19], 3.18mm [35], 10mm [20], and 22.5mm [6]) meet this tendency. This curve illustrates a method of minimizing the void content by adjusting the modified capillary number into the process window. However, even if it had been demonstrated that the void content can be reduced by optimizing the modified capillary number, the minimal void content cannot drop to zero in the case of bidirectional fabrics [5]. This is because keeping the flow fronts between the channels and in all yarns in different orientations same is impossible as yarns arranged in different orientations (e.g., warp and weft) coexist in the reinforcement.



**Figure 2.5:** Void content as a function of  $C_a^*$  [6].

**Figure 2.6:** Two resin flows between fibre tows and in the fibre tow [7].

A popular approach to model the formation of multi-scale voids has been reported by a number of researchers [6–8]. In this approach, the resin is considered to flow in dual scales shown in Figure 2.6. One flow is in the open gap at the meso scale, which is computed by Darcy's law in Equation 2.4. The other one within yarns is calculated by the capillary wicking through a porous zone and modified capillary pressure by Darcy's law at the resin-air interface in Equation 2.5. The capillary wicking is the main flow nature at the micropores inside the tow [7].

$$\frac{dl_C}{dt} = -\frac{\kappa_M}{\eta} \frac{\partial P}{\partial x} \tag{2.4}$$

$$\frac{dl_T}{dt} = -\frac{1}{1 - V_{f,T}} \frac{\kappa_T}{\eta} \left( \frac{\partial P}{\partial x} - \frac{P_{cap}}{l_T} \right)$$
(2.5)

where  $l_C$  and  $l_T$  are the flow front locations between yarns and in yarns, shown in Figure 2.6.  $\kappa_M$  is the permeability of the fabric between yarns and  $\kappa_T$  is the permeability in yarns.  $V_{f,T}$ is the fibre volume per yarn and  $P_{cap}$  [36] is the capillary pressure within yarns Equation 2.6.  $L_T$  in Figure 2.6 is the single tow length or the distance between the tow adjacent stitches. The pressure gradients  $\frac{\partial P}{\partial x}$  in Equations 2.4 and 2.5 are regarded as the same between yarns and in yarns.



**Figure 2.7:** Void formation mechanism [8]: (a) micro void formation situation, (b) macro void formation situation, and (c) no void situation.

$$P_{cap} = \left(\frac{F}{d_f}\right) \frac{V_{f,T}}{1 - V_{f,T}} \gamma \cdot \cos\theta_c \tag{2.6}$$

where F is the form factor depending on the fibre alignment and the flow direction. For the unidirectional fibrous preform, F is assumed as 4 in longitudinal direction and 2 in transverse direction. For the complex fibre alignment, such as the woven fabric, F is normally indirectly determined by measurements of the permeability.  $d_f$  is the diameter of a single fibre filament in meter.

Assuming the global pressure gradient is constant for a short period, two time scales of the resin flow through a single tow length  $L_T$  can be analytically obtained.  $\Delta t_C$  is the one between yarns and  $\Delta t_T$  is the other one within yarns. Consequently, there are three situations shown in Figure 2.7 summarized as the following relations:

$$\Delta t_T > \Delta t_c : V_a = h_{v,T} \cdot v_T \cdot (1 - V_{f,T}) \left( 1 - \frac{\Delta t_C}{\Delta t_T} \right)$$
(2.7)

$$\Delta t_T < \Delta t_c : V_a = h_{v,C} \times (1 - V_T) \left( 1 - \frac{\Delta t_T}{\Delta t_C} \right)$$
(2.8)

$$\Delta t_T = \Delta t_c : V_a = 0 \tag{2.9}$$

where  $V_a$ ,  $V_T$ ,  $h_{v,T}$ , and  $h_{v,C}$  are the void content, the tow volume, form factors in yarns and between yarns, respectively, which are the properties of the fabric. Gueroult [7] experimentally validated the analytical approach and demonstrated the comparison in Figure 2.8. The analytical approach was further improved by Park [17] considering the flow direction, void compression, and void transport. By the one dimensional filling simulation, the results successfully represented the correlation of void formations inside tows and between tows with modified capillary number and the influence of vacuum application at the air vent on the tow saturation and bubble compression. It is noticed that even if this approach is called as an analytical mathematical approach it is required some experimental parameters (e.g., permeabilities, form factors).

There are also some experimental curves [37–39], which merge the capillary number with the void percentage. Corresponding experimental equations for the bidirectional stitched



**Figure 2.8:** Model prediction and experimental measurement of multi-scale voids formation in RTM process [7].

fibreglass mat, the continuous random fibreglass mat, and the 4 harness woven fibreglass mat were developed by Patel and Lee [39].

$$V_M = -A - B * \log\left(\frac{Ca^*\gamma cos\theta}{\mu}\right)$$
(2.10)

$$V_m = A' - B' * \log\left(\frac{Ca^* \gamma cos\theta}{\mu}\right) \tag{2.11}$$

where  $V_M$  is the void percentage of macro voids and the  $V_m$  is the void percentage of micro voids. Parameters, A, B, A', and B', depend on the materials and the weave patterns.

The void percentage can also be represented as a function of the injection velocity. Some of them are from in-situ experiments, which can help to measure changes in the distribution of the void content during the filling and curing processes [20,40]. However, a more complex high resolution video-assisted microscopy is required for this in-situ observation [20,26]. Kang [41] also proposed a mathematical model to analyze the number of voids per square millimeter for 3mm thick laminates. This investigated model is used to optimize the flow velocity with respect to the fabrics geometric and the flow direction. However, the viscosity in this analytical model is constant and the effect of changing viscosity due to the time and temperature is not included, which leads to some error comparing with experiment results. Researches were also investing into the void size for various thickness (e.g., 3mm [19], 3.18mm [42], and 5mm [43]). Youssef [42] found the void content in a eight plies laminate varies up to 17% through the thickness. The size near the surface is larger than that interior. And the shape of the voids also varies from circular to elliptical. It is proved that the distribution and shape of voids are complex.

According to American aeronautics standard, final components should be rejected if there is more than 2% of voids [17], which influences the ILSS and easily leads to delaminations or disbonds. The ILSS dropped from 120 MNm<sup>-2</sup> to 98 MNm<sup>-2</sup> with the voids increasing from 0.5% to 1.5% [44]. The Young's modulus of the specimens reduces from 20.6GPa to 17.6GPa when the void content increases from 0 to 5% [45].

Therefore, the manufacturing parameters should be carefully designed and controlled and the effect of the void defect should be included into the final FE simulation since they dictate overall performance of the product.

### 2.4 The State-of-the-art Software

The simulation of the LCM processes is widely used with respect to the Finite Element/-Control Volume (FECV) and the Volume of Fluid (VOF) methods. In this section, some off the shelf softwares/codes (i.e., Liquid Injection Molding Simulation (LIMS) [6,30], PAM-RTM [46], and SimLCM [47]) to predict the sizes and locations of voids are introduced.

**LIMS** is developed by the University of Delaware and now Convergent software company holds its license. The numerical simulation LIMS [48] can simulate the fibre tow saturation. The output of the simulation includes the average void percentage. The modeling does match the trend experimentally observed in different specimens qualitatively [49]. LIMS can predict the dynamic void content in LCM processes by the introduction of the critical pressure for the void formation. However, this numerical procedure mainly focuses on Two-Dimensional (2D) and One-Dimensional (1D) elements. The numerical results generated by LIMS is normally then modified by corresponding experimental data [30, 50–53].

SimLCM is developed by the University of Auckland, which is based on the VOF method. The university of Auckland [47] includes the thermal transmission and the compression in it. Based on ANSYS Fluents, some researchers [54–57] also used the VOF method to model the filling process. Normally, only 2D situations are considered in this method [58]. Considering Three-Dimensional (3D) problems with complex geometries, although it is possible to use Fluents to simulate, researchers prefer verified the numerical models by comparing their results with the solution obtained in a dedicated software called PAM-RTM [59].

**PAM-RTM** developed by ESI group is part of PAM-COMPOSITES commercial software. ESI PAM-COMPOSITES is a FE simulation chain for the modeling of the manufacturing processes of composite structures and components. It is usually used for the simulation and optimization of manufacturing processes (i.e., the filling and curing process) with the objective of minimizing manufacturing time and defects and improving product qualities before cutting tool and real fabrication. PAM-RTM is part of the software suite, used to address the LCM application (like RTM, Vacuum Assisted Resin Infusion (VARI) and Compression RTM (C-RTM)). It can predict how the resin flows in the reinforcement and how long it takes to infuse the whole dry fabric. Typical results of the simulation are void percentage, pressure distribution, and viscosity distribution.

The obtained void information is then embedded into a FE model in ABAQUS to simulate the changes of mechanical properties in macro scale. However, the conversion of the simulation results into the mechanical properties is not done automatically in the above commercial codes. As the number of multi-scale voids is over thousands, creating thousands of holes

with variable volumes and locations in a single FE model is time-consuming. Thus, series of multi-scale MVE models to represent various void percentage at different locations are required.

Zhang [60] developed an effective method to generate composite MVE model based on Python-ABAUQS. The fibre volume fraction can be up to 65%. However, these MVE models only included two phases (i.e., the resin and fibres). Voids were not embeded. In order to have three phases (i.e., the resin, fibres, and multi-scale voids) coexist, **Digimat** is selected in this research. It is a commercial software from e-Xstream engineering, which is a spin-off from the University of Louvain. Digimat is a multi-scale material modeling platform for predicting the multi-scale behaviour of materials. Digimat-FE is part of it. It can generate MVEs based on material input (e.g., plastics, rubbers, metals, graphite) and micro-structure definition. More convenient is that the generated models and results can be used in external FEA codes, such as ABAQUS, ANSYS, LS-Dyna. Spoonire [61] successfully used Digimat to create batches of MVE models to study the effect of void content at the micro level and predict the stiffness of the part. Besides, Digimat can also obtain some failure characteristics of composite components [62].

### 2.5 Summary and Proposal

Some key points from literature study are summarized here:

- 1. Thick composites are the parts which can have a local temperature overshoot due to the chemical reaction during the curing process.
- 2. Macro- and micro voids in meso- and micro scales are the core of this research. Their creation, size, and distribution through a part are complicated and influenced by many parameters.
- 3. The changes in mechanical properties because of the voids should be carefully controlled to avoid having to reject parts because of poor mechanical performance due to excess voids. The capillary number is a common parameter used to analyze the void content.
- 4. LIMS, SimLCM, and PAM-RTM are current softwares to simulate LCM processes. PAM-RTM is available for 3D simulation. Digimat is used to build MVE models for the material behavior simulations in micro- and meso scales.

In order to achieve the objective mentioned in 1.2, the proposed methodology for this research is described. The filling process is simulated by the commercial code PAM-RTM in order to simulate 3D thick laminates. The input data is from the literature and material data sheets. After obtaining the void information related with the sizes and locations from PAM-RTM, the material behaviour will then be simulated in Digimat at micro and meso scales, which is offered by e-Xtream. All of them will be rearranged in the input file of ABAQUS for future mechanical analysis at macro scale. Finally, the stiffness range of composite laminates due to mutil-scale voids and increasing thickness will be obtained.

# Chapter 3

## Simulations

In this chapter, simulation methods are developed to analyze the filling process and caused voids. The overview of the simulation methods is shown in Figure 3.1. Based on the literature study, the filling process would be simulated first by PAM-RTM and described in Section 3.1. The output (sizes and locations of multi-scale voids) of the simulation would be analyzed and processed by Digimat and MATLAB. In Section 3.2, the material properties in micro-and meso- scales would be simulated by Digimat. In Section 3.3, the material properties for each element set (including multi plies) would be calculated by MATLAB and validated by corresponding ABAQUS simulations. After that, the rewritten elements, element sets, and their material properties would be rearranged in the input file of ABAQUS. The last step of the simulation is to build a macro scale FE model in ABAQUS, which would be used to simulate the stiffness losses for the whole thick laminate with multi-scale voids.

### 3.1 Filling Process Simulations Using PAM-RTM

The purpose of this section is to determine the parameters for the filling process simulations, based on the literature study and related material data sheets. The dimension of the simulation model is  $590 \text{mm} \times 330 \text{mm}$ . The materials are RTM6 (the resin) and TEN CATE®CD202 (the fabric). The properties of them are introduced in Section 3.1.1. As the filling process is controlled by many manufacturing parameters, this research concerns 6 major variables, described in Section 3.1.2 The simulation results are analyzed and discussed in Section 4.1.

### 3.1.1 Materials Selection

#### RTM6 (Resin)

As the baseline of the literature study, the resin system should have the capability to minimize the temperature overshoot and exothermal effects. A premixed, mono-component epoxy system, HexFlow RTM6 [9] produced by Hexcel, is selected. Compared with the two-component



Figure 3.1: Simulation flowchart for this research.

Cured resin density	Injection pressure	Preheat resin temperature	Tensile modulus
$1.14 \text{ g/cm}^3$	1  to  5  bar	$80^{\circ}\mathrm{C}$	2890MPa
Cure cycle	Strain	Preheat mould temperature	Tensile strength
$120$ min at $180^{\circ}$ C	3.4%	$120^{\circ}\mathrm{C}$	75MPa

Table 3.1: RTM6 product data [9].

Complex viscosity (Pas)



Figure 3.2: RTM6 Isothermal viscosity [9].

epoxy RTM6-2, RTM6 has less pretreatment steps for mixing. Related properties are listed in Table 3.1 and Figure 3.2.

The density used in this research is the cured one,  $1.14 \text{ g/cm}^3$ , instead of the uncured one  $1.11 \text{ g/cm}^3$ . The viscosity is changing with the various temperature and injection time. In order to have a longer injection time for fully infusing the dry fabric, the injection temperature is better to be lower than  $140^{\circ}$ C.

#### TEN CATE®CD202 (Reinforcement)

Since the diameter of the carbon fibre (normally 5 - 10  $\mu$ m) is smaller than that of the glass fibre (normally 16 - 24  $\mu$ m), the wetting area of carbon fibres is 3 times higher than that of glass fibres, which makes carbon fibre having a better permeability. TEN CATE®CD202 thus is selected for this research. The fabric has a dry weight of 200 g/m<sup>2</sup> in 2/2 Twill plain. The geometry is shown in Figure 3.3. There is 5 yarns per centimetre. Each yarn has 3K single fibre in the warp and the weft.



Figure 3.3: Geometry of 2/2 Twill plain TEN CATE®CD202.

#### 3.1.2 Variables

The focus of this research is mainly on the thickness, increasing from 20mm to 40mm. Besides, three injection strategies are analyzed, shown in Figure 3.4. The strategy one has the main resin flow in plane. The main resin flow in strategy two and three is through the thickness. The strategy two has the resin flow from the top to the bottom. The inlet is in the middle of the top surface. In contrast to the strategy two, the outlet of the strategy three is in the middle of the top surface. The inlet of this strategy is from the bottom.



Figure 3.4: Three injection strategies (the inlet is in green and the outlet is in blue).

As the fibre volume has influence on permeabilities, shown in Figure 2.2, it is considered to simulate these strategies with various fibre volume fractions. For LCM, the fibre volume fraction is normally in the range of 30 to 65% [30, 63-65]. In this research, the fraction of 55%, 60%, and 65% would be simulated respectively. Correspondingly, the permeabilities in different directions would be changed. The simulated values are listed in Table 3.2. In each direction, there are three values considered. The middle one is regarded as the reference. As the increasing filling temperature would softened the resin system and make it easy to flow, this research concerns three temperatures with variant viscosity from Figure 3.2. Besides, there are three injection pressures applied respectively to analyze the influence of the injection pressure on the void content.

There are two thicknesses, three injection strategies, three fiber volumes, three filling tem-
Fibe	er volun	ne $V_f$	Filling temperature			Injection pressure $P_{inj}$		
	(%)		(degree)		(bar)		r)	
55	60	65	100	120	140	2	4	6
Peri	neabilit	ty $\kappa_1$	Per	rmeabili	ity $\kappa_2$	Ι	Permeab	ility $\kappa_3$
$(\times$	$10^{-11} r$	$n^{2})$	()	$\times 10^{-11}$	$m^{2})$		$(\times 10^{-1})$	$^{3} m^{2}$ )
1.5	2.25	3	0.5	1.25	2	0.5	1.25	2

Table 3.2: Variables for simulation (unit) reference.

peratures, three injection pressures and night permeabilities. Totally, 648 (= $2 \times 3 \times 3 \times 3 \times (3 + 9)$ ) cases were ran. When studying the influence of these parameters, one is treated as the variable, while the others are constant, shown in Table 3.2. This means, for example, when the discussion focuses on the fibre volume, the filling temperature would stay on **120 degree**, the injection pressure would be **4 bar**.

After these simulations, the micro and macro void percentage at each point and the coordinate of each point are obtained. The percentage of each point is different, which means the material properties of each point are varying. The material properties of each point with varying micro and micro void percentages are simulated by Digimat and described in next section.

## 3.2 Microscale and Mesoscale MVEs Simulations Using Digimat

In this section, Digimat is used to simulate the material properties of a single fabric ply with multi-scale voids at micro- and meso scales. The classification of scales and corresponding voids are listed in Table 2.2.

No matter micro or macro voids in which scales, voids are in the resin system instead of in the single fibre. The micro voids would be embedded in the resin system first without fibres. These models only have two phases, micro voids and the resin. After that, the material properties of the resin with micro voids are obtained. The resin with micro voids is then regarded as a new degenerated resin. This new degenerated resin is considered as one phase and used as the input for the macro voids simulation. This means the following simulation also only includes two phases, the degenerated resin and macro voids. After that, properties of the softened resin with micro and macro voids are obtained. Combining with the fibre properties, the properties of the composites (including the softened resin and fibres) would be simulated.

It is noticed that in each single ply, yarns include both the softened resin phase and fibre phase. This means yarns already include multi-scale voids. Future description and explanation are in Section 3.2.3. Material properties of yarns also change with the changing multi-scale voids.

Following this process, the micro and macro voids would be embedded in a single fabric ply and the material properties would be obtained. The simulation processes are simply shown in Figure 3.5. More details are described below.



Figure 3.5: The overview of Digimat simulation work processes.



**Figure 3.6:** Geometries of micro-MVE models with varied void volumes, from 0.1% to 10%, where the MVEs dimension are  $50 \times 50 \times 50 \mu m^3$  and the fixed void diameter is  $4\mu m$ .

#### 3.2.1 Micro-MVE Models with Micro Voids

**Step a:** The effect of the micro voids is considered first. The MVE model has the dimension of  $50 \times 50 \times 50 \ \mu\text{m}^3$  and the diameter of micro voids is fixed at 3.90796  $\mu\text{m}$ , which is smaller than that of the carbon filament (7  $\mu\text{m}$ ). The diameter is chosen with a high precision in order to ensure that the void volume fraction remains as close as possible to the aimed void volume fraction. For example, when the diameter of micro voids is set up as 4  $\mu$ m instead of 3.90796 $\mu$ m, the actual void volume would be 33.510  $\mu$ m<sup>-3</sup> instead of 31.250  $\mu$ m<sup>-3</sup>. When the aimed void volume is 0.05% and the number of the voids is two, the actual void percentage would be 0.054% instead of 0.050%, which can cause more error.

In the micro MVE models there are two phases representing the resin and micro voids. The volume of the micro-void phase increases from 0 to 5%. Consequently, the volume of the resin phase reduces. The increase step of the void phase volume is 0.05%, from 0% to 1%. From 1% to 5%, the increase step is 1%. When the void volume is over 1%, the increase step is coarse as the predicted void percentages from the PAM-RTM are all smaller than 0.5%. In other words, it is possible for laminates to have more than 1% voids. However, with the parameters shows in Section 3.1, these cases simulated in this research only have voids with less than 0.5% multi-scale void percentages. Therefore, the Digimat simulations with the void percentage. This research mainly focuses on the range of 0 to 0.5%. In this step, 24 cases of micro-MVE models with varying micro-void percentages are simulated by Digimat. In Digimat, the geometries, shown in Figure 3.6, and the mesh steps can be generated based on the set material properties and phases.



**Figure 3.7:** Young's modulus (MPa) and Shear modulus of micro-MVE models with increasing micro-void volume fraction, from 0.1% to 5%, where the MVEs dimension are  $50 \times 50 \times 50 \mu m^3$  and the fixed micro-void diameter is 3.90796  $\mu m$ .

After that, the material properties (i.e., Young's Modulus, Poisson's Ratio, and the Shear Modulus) are automatically evaluated as a feature in Digimat. In Figure 3.7, the reduction of the Young's modulus and Shear modulus with the increasing micro-void percentage from 0.1% to 5% are illustrated. As the micro voids in the micro-MVE models are distributed randomly and the void volumes are small, the micro-MVE models are regarded as homogeneous. Besides, the almost invisible differences of Young's Modulus (or Shear Modulus) among different directions (e.g., E1, E2, E3) also can prove that the micro-MVE models is homogeneous, illustrated in Figure 3.7. Therefore, for the following simulations, the values of the material properties use the average in the three directions.

In Table 3.3, the decreasing percentages of material properties of micro-MVE models with increasing percentages of micro voids are listed. The descent percentages given are the differences of the new values from the original values When the percentage of micro-void phases increases to 0.5%, the Young's Modulus has a 1.183% decline and corresponding percentage reduction of the Shear Modulus is 0.98%. When it increases to 5%, the reduction of the Young's Modulus is 0.98%. When it increases to 5%, the reduction of the Young's Modulus is 0.98%. When it increases to 5%, the reduction of the Young's Modulus is still larger than that of the Shear Modulus, 8.453% and 7.854%, respectively. By contrast, the reduction of the Poisson's Ratio is smaller, even if the micro-void volume increases to 5%. The effect of micro voids on the resin system is large and cannot be ignored.

**Table 3.3:** The decreasing percentages of the material properties of micro-MVE models with micro voids.

Micro and macro void percentage (%)	0.5	1	5
Young's Modulus	1.183%	2.003%	8.453%
Poisson's ratio	0.567%	0.767%	2.133%
Shear Modulus	0.980%	1.763%	7.854%

**Step b:** Because the diameter of the micro voids at micro scale is not fixed, this step is aimed to check if it is necessary to include the effect of varying diameters of the micro voids. In this part, 4 different groups (i.e.,  $100 = 4 \times 25$  cases) micro-MVE models with diverse diameters of micro voids are built and simulated. The diameters of micro voids are in the range of 3.90796  $\mu$ m to 31.2636  $\mu$ m. The diameters are chosen in this range in order to keep the voids observed at micro scale and have the values near to the diameter of the single carbon fibre. The dimensions of the micro-MVE models and corresponding micro-void diameters are listed in the Table 3.4.

Dimension of the MVE model $(\mu m^3)$	Diameter of the micro void $(\mu m)$
	3.90796
$100^{3}$	7.81592
$200^{3}$	15.6318
$400^{3}$	31.2636

Table 3.4: Dimensions of micro-MVE models with corresponding micro-void diameters.

The MVE dimension is not fixed for different void diameters. If the dimension is fixed as  $400^3 \mu m^3$ , the number of voids is over 102,400 when the void volume is 5% and the void diameter is 3.90796  $\mu m$ . This would lead to a model crash during the simulation. If the dimension of the MVE is always small as  $50^3 \mu m^3$ , it is impossible to contain at least one void with the diameter over 30  $\mu m$  when the void volume is 0.05%. Not to mention that the MVE models needs to contain more voids when the void volume is 5%.



**Figure 3.8:** Young's Modulus (MPa) of micro MVE models with changing void volume and void dimension, from 0 to 5%.



**Figure 3.9:** Shear Modulus (MPa) of micro MVE models with changing void volume and void dimension, from 0 to 5%.

In Figure 3.8 and 3.9, the reduction of the material properties is illustrated with the increasing micro-void percentage from 0 to 5%. When diameters of voids are various, the reductions for each material properties are similar. For Young's Modulus, the maximum is 2666.7 MPa when the micro void volume is up to 5%. At this moment, the diameter of the void is 15.6318

 $\mu$ m. The minimum is 2645.6 MPa when the micro void volume is up to 5%. At this moment, the diameter of the void is 31.2636  $\mu$ m. The deviations among different groups are smaller than 0.791% when the micro void percentage is up to 5%. Therefore, the effect of varying diameters of the micro voids on the mechanical properties can be ignored. For the following simulation, the material properties of the 50<sup>3</sup> $\mu$ m<sup>3</sup> MVE models would be used.

#### 3.2.2 Meso-MVE Models with Macro Voids

**Step c:** Above, only micro voids are considered. The new reduced (degenerated in Figure 3.5) properties of the resin with micro voids are evaluated, which are used as the input for the following macro voids simulations at the meso scale. This means when simulating the macro voids, micro voids are represented by intact resin with reduced material properties but not as specific voids with certain diameters. In Digimat, there are still only two material phases created. One is the modified resin and the other one is representing the macro voids. In this step, the MVE models have the dimension of  $1.282^3 mm^3$  and the void diameter is 0.100mm.

In Figure 3.10 and 3.11, the reduction of the material properties due to the macro and micro voids are illustrated with the increasing macro- and micro-void percents in the range of 0 - 5%. It is noticed that the reductions due to the micro voids and micro voids are similar when the void percentages in two scales are same. For example, when the model only has the micro voids without macro voids and the void percentage is 5%, the Young's Modulus is 2645.7 MPa. When the model only has the macro voids without micro voids and the void percentage is 5%, the Young's Modulus is 2647.9 MPa. This means, the sizes of the voids are not the key point for the changes of Young's Modulus. It is important to include the multi-scale void percentages for the moduli simulations. However, it should be noticed that if the research has the purpose related with fatigue, it is better to include the sizes of voids as they may be the initial cracks or possible lead to delaminations.



**Figure 3.10:** Young's Modulus of models with macro and micro voids from 0 to 5%.



**Figure 3.11:** Shear Modulus of models with macro and micro voids from 0 to 5%.

Both Young's Modulus and Shear Modulus have a over 15% reduction when percentages of the multi-scale voids (i.e., macro voids and micro voids) are up to 5%, shown in Table 3.5. The effect of muti-scale voids on the Poisson's ratio is small, comparing with the decrease of other moduli.

**Table 3.5:** The decreasing percentages of the material properties of models when the micro and macro void percentage increases to 0.5%, 1%, and 5%.

Micro and macro void percentage $(\%)$	0.5	1	5
Young's Modulus	2.450%	3.976%	16.031%
Poisson's ratio	1.167%	1.467%	4.067%
Shear Modulus	2.141%	3.590%	15.112%

Combined with the macro voids, the resin properties have a further degeneration, which would be regarded as the softened resin system. This means, in the following simulation, no specific phase is used to represent multi-scale voids. The multi-scale voids are represented by the softened resin system as one phase.

#### 3.2.3 Meso-MVE models with Fabric

**Step d:** In this step, the properties of the fabric with the softened resin (including micro and macro voids) are evaluated. In Digimat, there are two material phases created in this meso-MVE model. One is the softened resin and the other is the carbon fibre.

The properties of softened resin (i.e., Young's and Shear Moduli) with specific micro and macro-void percentages are read off from Figure 3.10 and 3.11 in last Section. For example, if the simulated ply has 0.3% micro voids and 0.2% macro voids, the new values for the Young's and Shear Moduli of the resin phase can be picked up from above figure.



Figure 3.12: Geometries of the meso-MVE models: [0/90] layer (left), [45/-45] layer (right).

The carbon fibre used in this project is T300 and the material properties are listed in Table 3.6 [11]. Besides the matrix phase (the softened resin), the yarn is created with the linear density of 198 tex (g/km) and the fibre diameter of 0.007 mm. The fibre volume fraction for this yarn

Density	Axial Young's Modulus	In-plane Young's Modulus
$1.76 \mathrm{~g/cm^3}$	230  GPa	$40 { m GPa}$
Transverse Shear Modulus	Transverse Poisson's ratio	In-plane Poisson's ratio
30  GPa	0.25	0.3

Table 3.6: Material properties of T300 carbon fibre [11].

is 74.597%. The height of the yarn is 0.100mm and the width is 1.920mm. The geometry of the [0/90] single layer is shown in Figure 3.12-(left).

Due to the reduced material properties of the resin with the increasing micro and macro voids, the yarn properties also experience a decline, shown in Table 3.7. This is because yarns are made up of the resin and yarns. Although fibres do not change due to the multi-scale voids, material properties of the resin have a reduction with the increasing void percentages, shown in Section 3.2.2. As a result of the Digimat simulation, the in-plane Young's modulus has a 12.799% reduction when the multi-scale void percent is up to 5%, shown in Table 3.7. However, the axial Young's modulus is less effected due to the high stiffness of the carbon fibre. It only has a 0.070% decline from 172,310 MPa to 172,190 MPa when the multi-scale void percentage increases to 5%. This is because of fibres in axial can carry much loads and do not be affected by multi-scale voids.

Then, using these phase properties, the fabric structure is built. The fabric type used for [0/90] layer is 2D woven. For [45/-45] layer, only the fabric type is changed as braided in order to directly evaluate material properties in  $45 \circ$  direction. There is no insert inlays to ensure the fabric structure is same with that of the [0/90] layer. The braiding angle can be set in the interval [1,89] in Digimat. When the angle is set as 45, the only difference between [0/90] layer and [45/-45] layer is the principle direction, shown in Figure 3.12-(right). Both weave patterns are 2/2 twill according to the material, and the geometry is shown in Figure 3.3. The dimension is  $8 \times 8 \times 0.2$  mm<sup>3</sup> for the [0/90] layer, and is  $5.657 \times 5.657 \times 0.2$  mm<sup>3</sup> for the [45/-45] layer. For the [45/-45] layer, the unit cell (MVE) size is same with that for the [0/90] layer. Digimat then automatically evaluates the fabric properties combining the resin properties in the matrix phase and the yarn properties in the fibre phase. All of them have same yarn properties and matrix properties with certain micro- and macro-void percentage. The blue yarn is the warp yarn and the yarn count is 5 yarns/cm. The red one is the weft yarn with the same count. The matrix phase is in and between each yarn and within each yarn. The outputs of these simulations are shown and analyzed in Section 4.2.

Micro and macro void percentage $(\%)$	0.5	1	5
Axial Young's modulus (MPa)	0.012%	$\begin{array}{c} 0.017\%\ 3.170\%\ 1.066\%\end{array}$	0.070%
In-plane Young's modulus (MPa)	1.990%		1 <b>2.799%</b>
In-plane Poisson's ratio	0.871%		2.730%

**Table 3.7:** The decreasing percentages of the yarn properties when the micro and macro void percentage increases to 0.5%, 1%, and 5%.

## 3.3 Macroscale Laminate Simulations Using ABAQUS

The purpose of this section is to transfer the model information (i.e., node, element, material properties of each element set) from PAM-RTM to ABAQUS, combining the material properties of each ply in Section 3.2. After that, the FEM in ABAQUS can be built to evaluate material properties of the thick laminates at the macro scale.

#### 3.3.1 Element

This subsection focuses on transferring elements from PAM-RTM to ABAQUS. Each element in both PAM-RTM and ABAQUS includes several nodes. Each node has its unique coordinate. In ABAQUS, each element is expected to have 8 nodes and to have the aspect ratio close to 1. In the following processes, nodes from PAM-RTM are used to write the new elements in ABAUQS which have the aspect ratio close to 1.

The models in PAM-RTM have two dimensions. One is  $590 \times 330 \times 20 \text{ mm}^3$  and the other one is  $590 \times 330 \times 40 \text{ mm}^3$ . In PAM-RTM, the in-plane mesh size is 14 mm by 14 mm and the in-plane aspect ratio is 1. The mesh size along the thickness is dependent on the thickness per ply. In this research, the thickness per ply is 0.2 mm, which makes the out-of-plane aspect ratio over 70. If the in-plane mesh size is set as 0.2 mm by 0.2 mm, the number of the elements would be over 4.8 billion, which is out of memory for ABAQUS. When the in-plane mesh size is 14 mm by 14 mm, the filling process simulation already converges in PAM-RTM. So it is not necessary to reduce the in-plane mesh size. In order to have the out-of-plane aspect ratio close to 1 in ABAQUS, elements should be rewritten. 50 elements along the thickness are grouped together, which makes the new grouped element having the dimension of  $14 \times 14 \times 10$ mm<sup>3</sup>. Now, the new created elements have the out-of-plane aspect ratio close to 1, comparing with the original one.

In ABAQUS, the mesh size should be small enough for converging the simulation results. Instead of grouping 50 elements along the thickness, there is a verification case which groups 10 elements together. Each element in Figure 3.13-(d) has the dimension of  $14 \times 14 \times 2 \text{ mm}^3$ . The out-of-plane aspect ratio is 7, which is larger than 1. The grouped elements are needed to be divided in to  $7 \times 7$  units to ensure each unit has the dimension of  $2 \times 2 \times 2 \text{ mm}^3$ , shown in Figure 3.13 (e). Only in this way, the out-of-plane aspect ratio of each element is equal to 1. Finally, 486750 elements are generated for the 20 mm thick laminate. After simulating in ABAQUS, the tensile Young's Modulus E1 of the 20 mm thick laminate is 48614.487 MPa when the mesh size is  $2 \times 2 \times 2 \text{ mm}^3$ . When the mesh size is  $14 \times 14 \times 10 \text{ mm}^3$ , the E1 is 48616.038 MPa. This means the model already converges when the mesh size of  $2 \times 2 \times 2 \text{ mm}^3$  in ABAQUS is time consuming. Therefore, computable and effective grouping size, 50 elements along the thickness, is used in this research.

#### 3.3.2 Material Properties of Each Element

Based on the material properties of each ply, the material properties of each element can be numerically calculated [66] by MATLAB or simulated by ABAQUS. These two approaches



Figure 3.13: Rewrite elements and make their aspect ratio equal to 1.

are introduced first. And a mutual verification example would then be described. As the deviation between these two approaches is small, the time-saving approach is used.

In MATLAB, the compliance tensor  $S_{ij}^k$  of each ply can be calculated by Equation 3.1, based on the material properties (i.e., Young's Modulus E, Poisson's Ratio  $\nu$ , and Shear Modulus G) from Digimat. After inverting by the Equation 3.2, the stiffness of each ply can be obtained. The compliance tensor of each element can be obtained by averaging these ply components, shown in Equation 3.3. Then, the material properties of each element can be derived as Equations 3.4 - 3.15.

$$\boldsymbol{S}_{ij}^{k} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & -\frac{\nu_{12}}{E_{11}} & -\frac{\nu_{13}}{E_{11}} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & -\frac{\nu_{23}}{E_{22}} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_{11}} & -\frac{\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$$
(3.1)

$$C_{ij}^{k} = S_{ij}^{k^{-1}}$$
(3.2)

$$C_{ij} = \frac{1}{n} \sum_{n=1}^{k=1} C_{ij}^k$$
(3.3)

$$\nu_{xz} = \frac{C_{12}C_{23}C_{66} - C_{13}C_{22}C_{66}}{C_{66}C_{23}^2 - C_{22}C_{33}C_{66}}$$
(3.4)

$$\nu_{xy} = \frac{C_{13}C_{23}C_{66} - C_{12}C_{33}C_{66}}{C_{66}C_{23}^2 - C_{22}C_{33}C_{66}}$$
(3.5)

$$E_x = C_{11} - \nu_{xy}C_{12} - \nu_{xz}C_{13} \tag{3.6}$$

$$E_y = C_{22} - \nu_{yz} C_{12} - \nu_{yz} C_{23} \tag{3.7}$$

$$\nu_{yz} = \frac{C_{12}C_{13}C_{66} - C_{11}C_{23}C_{66}}{C_{66}C_{13}^2 - C_{11}C_{33}C_{66}}$$
(3.8)

$$\nu_{yx} = \frac{C_{12}C_{13}C_{66} - C_{11}C_{23}C_{66}}{C_{66}C_{13}^2 - C_{11}C_{22}C_{66}}$$
(3.9)

$$E_z = C_{33} - \nu_{zx} C_{13} - \nu_{zy} C_{23} \tag{3.10}$$

$$\nu_{zy} = \frac{C_{12}C_{13}C_{66} - C_{11}C_{23}C_{66}}{C_{66}C_{12}^2 - C_{11}C_{22}C_{66}}$$
(3.11)

$$\nu_{zx} = \frac{C_{12}C_{23}C_{66} - C_{13}C_{22}C_{66}}{C_{66}C_{12}^2 - C_{11}C_{22}C_{66}}$$
(3.12)

$$G_{yz} = C_{44}$$
 (3.13)

$$G_{xz} = C_{55}$$
 (3.14)

$$G_{xy} = C_{66}$$
 (3.15)



Figure 3.14: The geometry of 1/8 laminate.

In ABAQUS, a multi-ply laminate can also be built with variable material properties. The material properties of each ply also use the properties from the Digimat simulation. 1/8 of a 20-ply laminate model, shown in Figure 3.14, would be simulated for different stiffness listed in Table 3.8. The layup  $[(45/-45)_4(0/90)_6]_s$  is symmetry. The remainder of the laminate is the same as the 1/8. There are totally 6 cases for each laminate to evaluate 12 stiffness parameters (i.e., three Young's moduli, three Shear moduli, and six Poisson's ratios). Each

Simulated Stiffness	xy-plane	xz-plane	yz-plane	Load
E1 $\nu 12\nu 13$	U3=0	U2=0	U1=0	Pressure on yz-plane
E2 $\nu 23, \nu 21$	U3=0	U2=0	U1=0	Pressure on xz-plane
E3 $\nu$ 31, $\nu$ 31	U3=0	U2=0	U1=0	Pressure on xy-plane
G12	U3=0	U3=0	U1,2,3=0	Surface traction on zy-plane
G23	U1,2,3=0	U1=0	U1=0	Surface traction on xy-plane
G13	U3=0	U1,2,3=0	U3=0	Surface traction on xz-plane

 Table 3.8:
 Boundary conditions and loads for simulating different stiffness.

**Table 3.9:** The results of the numerical calculation and the simulation of a  $[(45/-45)_4(0/90)_6]_s$  laminate.

	ABAQUS	MATLAB	deviation		ABAQUS	MATLAB	deviation
E1(MPa)	44318.7	44666.6	0.785%	$\nu 12$	0.315	0.311	1.554%
E2(MPa)	44054.9	44367.0	0.708%	$\nu 13$	0.261	0.258	0.959%
E3(MPa)	8694.5	8693.2	0.015%	$\nu 23$	0.261	0.268	2.584%
G12(MPa)	17074.3	16771.1	1.777%	$\nu 21$	0.316	0.308	2.435%
G23(MPa)	2868.6	2865.9	0.095%	$\nu 32$	0.052	0.053	1.905%
G13(MPa)	2849.6	2842.3	0.257%	$\nu 23$	0.051	0.050	1.761%

case has its corresponding boundary conditions and loads. The boundary conditions and the corresponding loads for simulating different stiffness are also listed in the Table 3.8.

**Verification** These two approaches are used to simulate a  $[(45/-45)_4(0/90)_6]_s$  laminate for the mutual verification. The input material properties are from Digimat. They are the material properties of a single ply without any voids. The results of the numerical calculation and the simulation are listed in the Table 3.9. The deviation between these two approaches is smaller than 2.6%. Especially for the modulus, most of the deviation is smaller than 1%. As the numerical approach calculated by MATLAB saves time, the material properties of each element are calculated by MATLAB.

#### 3.3.3 Input File for ABAQUS

Till now, the new generated elements and corresponding material properties are obtained. This data is rearranged into an input file for ABAQUS. An input file contains almost all the model information, including the definition and solution of the model and the output requirements, which would be submitted to ABAQUS solver [67]. An input file is divided into model data part and history data part, shown in Figure 3.15.

- The model data part includes the node, element, material, and initial condition. The *node data* is from PAM-RTM and each node has its own coordinate. The *element data* is generated by MATLAB and described in Section 3.3.1.
- The history data part includes the analysis type, loading, output requests.

The type of elements is a general purpose linear brick element, C3D8R with reduced integration (1 integration point). Due to the reduced integration, the locking phenomena observed in the C3D8 element does not appear. Hourglass control is automatically activated for this element and thus alleviating the hourglassing issue. As the bending is not included in this research, this element is stiff enough for high accuracy stresses and strains.



Figure 3.15: The structure of an input file.

The 'eset' is the element set that includes these elements which have same material properties. In this research, the same material properties mean each ply in each element has same macro and micro void contents. And the material properties of each 'eset' would be calculated by MATALB, described in Section 3.3.2. 3D solid section is used in this research.

After the instance, there are some nodes grouped together as 'nset' for applying the boundary conditions. The boundary conditions are listed in Table 3.8. For example, all the nodes whose x coordinates are equal to the minimum x coordinate are grouped together. And this 'nset' represents the surface of zy-plane. When calculating E1, this 'nset' is set as 'XSYMM' which means U1 is fixed.

The 'elset' in the 'assembly' part is different from the above one. The 'elset' here is used for applying loads. In this research, the loads are pressures and surface tractions, which are applied on the surface instead of nodes, shown in Table 3.8. For example, when calculating E1, all the elements that contain the nodes whose x coordinates are equal to the maximum x coordinate are selected first. Then, the surface which includes the nodes having the maximum x coordinate is selected.

At the end, the output requirements will be included. In this research, the outputs are the stress and strain of all the nodes of the thick laminates. After post-processing, the stiffness of the whole laminate will be obtained, including Young's Modulus, Poisson's Ratio, and Shear Modulus.

## 3.4 Summary

In this chapter, the simulation process is described. Based on the inputs of the material properties of the resin and the fabric, the filling process is simulated first by PA-RTM. The outputs of these simulations are the macro and micro void percentages and the coordinate of each node. The void information is used in Digimat to simulate the changes of mechanical properties of the single ply with mutli-scale voids in micro- and meso scales. The material properties of elements including 50 plies with various material properties would be numerically calculated by MATLAB. After that, combining with the coordinate of each node, an input file for ABAQUS including the model and history data parts are rewritten. This is used for macro simulation and finally to obtain the changing mechanical properties due to the multi-scale voids. The results are shown and discussed in next chapter.

# Chapter 4

# **Results and Discussion**

In this chapter, the simulation results are described and analyzed. Section 4.1 shows the outputs of the filling process simulation by PAM-RTM. The effect of each parameter on the void percentage of the thick laminates is illustrated. The discussion of the effect of multi-scale voids on one ply is included in Section 4.2. The changing mechanical properties of the thick laminate are introduced in Section 4.3. The solution approach in Chapter 3 is also verified by comparing it with results of experimental models [68] and is described in Section 4.4.

## 4.1 Filling Process Simulation

In this section, the results of the filling process simulation are analyzed. The filling process simulation considers six variables: thickness (20 mm and 40 mm), injection strategies (shown in Figure 3.4), fiber volume  $[V_f]$ , injection pressure  $[P_{inj}]$ , permeability  $[\kappa]$ , and filling temperature  $[T_f]$  (shown in Table 3.2). All the variables are analyzed in the following four subsections. Each section includes three variables: thickness, injection strategies, and one of the four variables (i.e.,  $V_f$ ,  $P_{inj}$ ,  $\kappa$ , and  $T_f$ ).

For the simulation of the 20mm thick laminates, the element number in PAM-RTM is 108,575 and for the 40mm thick laminate is 216,075. Each of them has its own micro and macro void volumes. In this section, the discussed output mainly focuses on the effect of each parameter on the void percentage values instead of the distribution (locations).

For each data figure in this section, the micro voids is represented as **colored solid line**. For the data of the macro voids, it is represented as **colored dotted line**. Each figure includes 4 main groups and 12 curves to present the relation between the variables and the micro/macro void percentage. The 4 main groups are the micro voids of the 20mm thick laminate, the macro voids of the 20mm thick laminate, the micro voids of the 40mm thick laminate, and the macro voids of the 40mm thick laminate.



**Figure 4.1:** Micro- and macro voids percentages per element when using different injection strategies with varied **fibre volume**  $[V_f]$  on 20mm and 40mm thick laminates (filling temperature: 120 degree, injection pressure: 4 bar, the permeabilites:  $2.25 \times 10^{-11}$ ,  $1.25 \times 10^{-11}$ , and  $1.25 \times 10^{-13}$  m<sup>2</sup>, respectively).

#### 4.1.1 fibre Volume

In this subsection, filling temperature, injection pressure, and permeabilities are fixed. Figure 4.1 shows that changing fibre volume  $[V_f]$  **does not** have influence on the void percentage, no matter which thickness the laminate has or which injection strategy the laminate uses. These three injection strategies are illustrated in Figure 3.4.

For example, for injection strategy one shown in Figure 4.1-(a), when the fibre volume increases from 55% to 65%, the micro/macro void percentage per element is same for the two thickness laminates. When the thickness is 20 mm, the micro void percentage is represented by solid lines and the macro void percentage is represented by dotted lines. The solid-line curves illustrating the micro void percentage per element with different fibre volume (i.e., the magenta solid line means the fibre volume is 65%, the green solid line means the fibre volume is 60%, and the blue solid line means the fibre volume is 55%, )are nearly complete coincidence. It proves that increasing the fibre volume does not affect the multi-scale void percentages.

The average macro void percentage per element for both thickness laminates and all different fibre volume laminates is constant, 0.287%, when using injection strategy one. In other word, the average values of all the dotted lines in Figure 4.1-(a) are same. This means increasing the thickness, the average multi-scale void percentage of the whole laminates is constant.

However, the void percentage per element for each injection strategy is different. For the 40mm thick laminates, when using injection strategy one, around half of the elements has the macro void volume close to 0.350%, and the average macro void percentage per element is 0.287%. The data is represented by the dotted lines with 216,075 elements in Figure 4.1-(a). For micro voids, 75% elements have a micro void percentage close to 0.200% and the average micro void percentage per element is 0.202%. The data is represented by the solid lines with 216,075 elements in Figure 4.1-(a). When using injection strategy two or three, most of the macro void percentages per element is close to 0.350% and the averages of them are 0.360% and 0.347%, respectively. The data is represented by the dotted lines with 216,075 elements in Figure 4.1-(b) and (c). For micro voids, they are all close to 0.200%. These results implies that when doing the macro-scale simulation, half of the laminate has same material properties when using injection strategy one, shown in Figure 4.2. For strategies two and three, most laminate elements have the same material properties, shown in Figure 4.3.

#### 4.1.2 Injection Pressure

In this subsection, filling temperature, fibre volume, and permeabilities are fixed. Figure 4.4 shows the injection pressure  $P_{inj}$  does have influence on the void percentage of the thick laminates.

First is to discuss the changing macro-void percentages due to the various injection pressures. They are represented by the dotted lines in Figure 4.4. When the injection pressure increases, there are less elements with a macro void percentage close to 0.35%, especially using injection strategy one shown in Figure 4.4-(a). This means increasing the injection pressure can lead to a reduction of the macro-void percentage per element. The tendency also can be verified by Equation 2.3. Increasing the injection pressure leads to a growing fluid front velocity. It



**Figure 4.2:** Elements with the macro voids of 0.287% and micro voids of 0.202% (yellow parts) when using injection strategy one.



**Figure 4.3:** Elements with the macro voids of 0.360% and micro voids of 0.200% (yellow parts) when using injection strategy two.

promotes the  $C_a^*$  to increase. When the  $C_a^*$  increases, the macro-scale void content reduces, shown in Figure 2.5.

At the same time, Figure 2.5 also illustrates that the increasing  $C_a^*$  can contribute to a larger micro-scale void content. This tendency can be observed in Figure 4.4 and is represented by the solid lines. However, the increasing micro-void percentages due to the increasing injection pressure are not well obvious, especially when using injection strategies two and three. This means the changing injection pressure has significant effect on the macro-void contents and has less effect on the micro-void contents. It is proved by the sharper slope of the macro-scale void content shown in Figure 2.5.

The average multi-scale void percentages of the thick laminates are listed in Table 4.1 when using injection strategy one. When the injection pressure is fixed, the increasing thickness leads to the growing void number but not change the average multi-scale void percentage. For example, when the injection pressure is 6 bar, the average micro-void percentage of the 20 mm and 40 mm thick laminates are both 0.206%. It proves that the laminate thickness **does not have influence** on the average multi-scale void percentage of the thick laminates.

**Table 4.1:** The average multi-scale void percentages of the 20mm and 40mm thick laminates when using **injection strategy one with various injection pressures** (filling temperature: 120 degree, fibre volume: 60%, permeabilites:  $2.25 \times 10^{-11}$ ,  $1.25 \times 10^{-11}$ , and  $1.25 \times 10^{-13}$  m<sup>2</sup>, respectively.

	20mm thick laminate		40mm thick laminate		
Injection Pressure (bar)	micro voids	macro voids	micro voids	macro voids	
6	0.206%	0.251%	0.206%	0.251%	
4	0.202%	0.286%	0.202%	0.287%	
2	0.198%	0.331%	0.198%	0.331%	

Increasing the injection pressure can help to reduce the filling time. For injection strategy one, when the injection pressure increases from 2 bar to 6 bar, the filling time reduces from 807s to 165s, listed in Table 4.2. The filling times for these cases are independent on the laminates thickness. In other word, when using injection strategy one, the filling time does



**Figure 4.4:** Micro- and macro voids percentages per element when using different injection strategies with varied **Injection pressure**  $[P_{inj}]$  on 20mm and 40mm thick laminates (filling temperature: 120 degree, fibre volume: 60%, permeabilites: 2.25 ×10<sup>-11</sup>, 1.25 ×10<sup>-11</sup>, and 1.25 ×10<sup>-13</sup> m<sup>2</sup>, respectively.

Injection Pressure	20mm thick laminate filling time (s)	40mm thick laminate filling time (s)	
6	165	165	
4	267	266	
2	806	805	

**Table 4.2:** The filling times of 20mm and 40mm thick laminates when using **injection strategy one with various injection pressures** (filling temperature: 120 degree, fibre volume: 60%, permeabilites:  $2.25 \times 10^{-11}$ ,  $1.25 \times 10^{-11}$ , and  $1.25 \times 10^{-13}$  m<sup>2</sup>, respectively.

**Table 4.3:** The filling times of 20mm and 40mm thick laminates when using **injection strategy two with various injection pressures** (filling temperature: 120 degree, fibre volume: 60%, permeabilites:  $2.25 \times 10^{-11}$ ,  $1.25 \times 10^{-11}$ , and  $1.25 \times 10^{-13}$  m<sup>2</sup>, respectively.

Injection Pressure	20mm thick laminate filling time (s)	40mm thick laminate filling time (s)	
6	1041	2220	
4	1798	4024	
2	6879	16770	

not change with the changing laminate thickness. This is mainly because the filling flow is in plane instead of through the thickness.

Table 4.3 lists the various filling times of 20mm and 40mm laminates due to the changing injection pressures when using injection strategy 2. It also proved that the increasing injection pressure could reduce the filling time. Besides, it is noticeable that the filling time increase when the thickness of the laminate increases, instead of keeping constant with increasing thickness when using injection strategy one. The reason is that injection strategy two mainly depends on the filling flow through the thickness. The permeability along the thickness is small, which means it slows the infusion speed. Therefore, when the thickness increases, the filling time consequently increases.

However, it should be noticed that the injection pressure cannot be increased infinitely for real applications with the purpose of reducing the filling time. Normally, high pressure on the resin system always needs a corresponding low viscosity of the resin in order to flow fast. Only if the temperature of the preheating resin and the mould are high, the viscosity could be low. But the temperature cannot be as high as possible. Otherwise, the resin is easily cured earlier before it fully infuses the fabric laminate. Due to the limitation of the maximum operation temperature, the injection pressure cannot be set too high.

#### 4.1.3 Permeability

In this subsection, filling temperature, fibre volume, and injection pressure are fixed. The purpose of this subsection is to discuss the effect of permeabilities on the multi-scale void percentage. The in-plane permeabilities  $\kappa_1$  and  $\kappa_2$  are similar for the composite woven. Here, only the results of the  $\kappa_1$  and the  $\kappa_3$  through the thickness are shown and discussed. Figure 4.5 includes three injection strategies, varied permeabilities, and different laminate



**Figure 4.5:** Micro- and macro voids percentages per element when using different injection strategies with varied **Permeability** [ $\kappa$ ],  $\kappa_1$  (left), and  $\kappa_3$  (right), on 20mm and 40mm thick laminates (filling temperature: 120 degree, injection pressure: 4 bar, and fibre volume: 60%.

thickness. Figure 4.5-(a) to (c) focuses on permeability  $\kappa_1$ . In these cases, only the  $\kappa_1$  is changing and the values are shown in Figure 4.5-(d). The  $\kappa_2$  is fixed as  $1.25 \times 10^{-11}$  m<sup>2</sup> and the  $\kappa_3$  is fixed as  $1.25 \times 10^{-13}$  m<sup>2</sup>. Figure 4.5-(e) to (g) focuses on the permeability  $\kappa_3$ . In these cases, only the  $\kappa_3$  is changing and the values are shown in Figure 4.5-(h). The  $\kappa_1$  is fixed as  $2.25 \times 10^{-11}$  m<sup>2</sup> and the  $\kappa_2$  is fixed as  $1.25 \times 10^{-11}$  m<sup>2</sup>.

For  $\kappa_1$ , when using injection strategy one, an increasing permeability  $\kappa_1$  has the same effect on the macro void percentage, shown in the Figure 4.5-(a) compared with the increasing injection pressure, shown in the Figure 4.4-(a). With the increasing permeability  $\kappa_1$ , the macro-void percentages reduce for both 20mm and 40mm thick laminates when using injection strategy one. When using injection strategy three, the trend is the same but is not clear like injection strategy one. For injection strategy two, the differences of the multi-scale void percentage are too small to observe, thus the effect of the permeability  $\kappa_1$  on the multi-scale void percentages can be ignored.

When using injection strategy one, an increasing permeability  $\kappa_1$  offers a faster flow in plane. This means that the filling time could be short with a higher permeability  $\kappa_1$ . In injection strategy one, the flow is mainly in plane. Therefore, the increasing thickness of the laminates does not have influence on the filling time. For both 20mm and 40mm laminates, the filling time decreases from 399s to 204s when the permeability  $\kappa_1$  increases from  $1.5 \times 10^{-11}$  m<sup>2</sup> to  $3 \times 10^{-11}$  m<sup>2</sup>.

For  $\kappa_3$ , when using injection strategy one, an increasing permeability  $\kappa_3$  has the same effect on the macro void percentage, shown in the Figure 4.5-(d) compared with the increasing fibre volume, shown in the Figure 4.1-(a). For injection strategy one and two, the differences of the multi-scale void percentage are too small to be observed and the effect of the permeability  $\kappa_3$ on the void percentage can be ignored. Even the differences of the macro-void percentage is visible when using injection strategy three, the deviation is still smaller than 0.01%. Therefore, the effect of the permeability  $\kappa_3$  on the multi-scale void percentage can be ignored no matter which injection strategy is applied.

Besides, as the order of magnitude of the permeability  $\kappa_3$  is too small, the effect of the permeability  $\kappa_3$  on the filling time also can be ignored when using injection strategy one. This strategy mainly relies on the flow in plane with the permeability  $\kappa_1$  instead of the out-of-plane permeability  $\kappa_3$ . For injection strategy two and three, the flow is mainly dependent on the out-of-plane permeability  $\kappa_3$ . The filling time is shorter when increasing the permeability  $\kappa_3$ . The filling time reduces at least half when the permeability  $\kappa_3$  increasing from  $0.5 \times 10^{-13}$  m<sup>2</sup> to  $2 \times 10^{-13}$  m<sup>2</sup>.

Overall, an increasing in-plane permeability can reduce the void percentage of the laminates whose in-plane resin flow is dominant. Similarly, an increasing out-of-plane permeability can reduce the void percentage of the laminates whose out-of-plane resin flow is dominant. At the same time, the filling time is reduced due to the increasing permeabilities.

#### 4.1.4 Filling Temperature

In this subsection, fibre volume, injection pressure, and permeabilities are fixed. The filling temperature means the temperature of the mould during the filling process. Figure 4.6 shows that the filling temperature **does not have any influence** on the multi-scale voids for both

20mm and 40mm thick laminates. However, the increasing filling temperature could reduce the filling time from 592s to 152s for both 20mm and 40mm thick laminates when using injection strategy one.



**Figure 4.6:** Micro- and macro voids percentages per element when using different injection strategies with varied **Filling temperature**  $[T_f]$  on 20mm and 40mm thick laminates (injection pressure: 4 bar, fibre volume: 60%, and permeabilites:  $2.25 \times 10^{-11}$ ,  $1.25 \times 10^{-11}$ , and  $1.25 \times 10^{-13}$  m<sup>2</sup>, respectively.

#### 4.1.5 Summary

Based on the output from PAM-RTM, the range of macro-void percentages is from 0 to 0.362%. For micro-void percentages, the range is in between 0.190 and 0.334%. For most of these simulations, more than half of the elements for each simulation have a macro-void percentage close to 0.35%. More than 75% of these elements for each simulation have a micro-void percentage close to 0.2%. Increasing the thickness, the average multi-scale void percentage does not change.

For injection strategy one, the fibre volume, the permeability  $\kappa_3$ , and the filling temperature do not have influence on the multi-scale void percentages. The increased injection pressure and the increased permeability  $\kappa_1(\kappa_2)$  can reduce the macro-void percentages. But the microvoid percentage only shows a slight change with these variables. All the variables have less influence on the multi-scale void percentages when using injection strategy two. For injection strategy three, the increased injection pressure and increased the permeability  $\kappa_3$  decrease the macro-void percentages for both 20mm and 40mm thick laminates. The difference of the micro-void percentages is not visible.

These variables also have some influence on the filling time. Normally, increasing one of these variables, the filling time reduces. However, the increased permeability  $\kappa_1$  has negligible influence on the filling time when using injection strategy one. The increased permeabilities  $\kappa_1$  and  $\kappa_2$ ) have no visible influence on the filling time when using injection strategy two or three. This is due to the main flow direction in each strategy.

## 4.2 Multi-scale Voids Simulation

In this section, the results of multi-scale void simulations are introduced. There are two main simulations for the [0/90] single layer in Section 4.2.1 and the [45/-45] single layer in Section 4.2.2. The comparison of these two kinds of single layer is discussed in Section 4.2.3.

#### 4.2.1 [0/90] Single Layer

For the [0/90] single layer, simulation results of meso-RVE models with both micro and macro voids are shown in Figure 4.7. With increasing multi-scale voids, all the material properties reduce. In Figure 4.7, the ranges of the macro- and micro-void percentages are all from 0 to 5%. In the range of 0 to 1%, the increment is 0.05%. In the range above 1%, the increment is 1%. The in-plane Young's modulus E1 and E2 are around 61GPa, and out-of-plane Young's modulus E3 is much smaller, around 8GPa, shown in Figure 4.7a and Figure 4.7b, respectively. The E1 and E2 are the in-plane modulus and they have a similar downtrend. Although both of them have a reduction over hundreds MPa, the decreasing percentage is small. In contrast, the reduction and decreasing rate are both larger for the E3. The Poisson's ratio  $\nu 13$  and  $\nu 23$  are much larger, around 0.35, shown in Figure 4.7d. The Shear modulus G12 is around 4GPa and the G13 and G23 are around 3GPa, shown in Figure 4.7e and Figure 4.7f respectively. All these material properties reduce due to the multi-scale voids.

In Table 4.4, some specific data is listed for analysis. The in-plane Young's modulus E1 and E2 have a small decreasing percentage, no more than 2%, even if the multi-scale void percentage is up to 5%. This is reasonable because it is fibre-dominant. Most of the load is carried by fibres instead of the resin system. Fibres are not damaged due to the multi-scale voids This is because all the voids are in the resin system. This can also be proved by the reducing percentages of the yarn properties with multi-scale voids in Table 3.7. The axial Young's modulus have less than a 0.1% reduction, even if the multi-scale void percentage increases to 5%. However, the out-of-plane Young's modulus E3 is affected by the multi-scale voids. The decreasing rate is more than 15% when the multi-scale void percentage is up to

macro and micro voids	0.5%	5%
E1(MPa)	0.294%	1.965%
E2(MPa)	0.297%	1.987%
E3(MPa)	2.587%	15.211%
G12(MPa)	1.813%	12.901%
G13(MPa)	1.960%	13.683%
G23(MPa)	1.960%	13.692%
v12	1.319%	6.653%
v21	1.322%	6.674%
v13	0.872%	2.747%
v31	3.152%	15.888%
v23	0.876%	2.7642%
v32	3.152%	15.884%

**Table 4.4:** Material properties decreasing percentages for [0/90] single layer, where both micro and macro voids increase to 0.5%, 5%.

5%. This is because the resin system is dominant in this direction. The decreasing percentage is close to the Young's modulus of the soften resin system in Table 3.5, 16.031% when the multi-scale void percentage increases to 5%.

#### 4.2.2 [45/-45] Single Layer

For the [45/-45] single layer, the simulation results of the meso-RVE models with both micro and macro voids are shown in Figure 4.8. With an increasing multi-scale voids, most of the material properties have a decline. In Figure 4.8, the ranges of the macro- and microvoid percentages are both from 0 to 0.5%. The in-plane Young's modulus E1 and E2 are around 15GPa, and out-of-plane Young's modulus E3 is much smaller, around 8GPa, shown in Figure 4.8a and Figure 4.8b, respectively. Compared with the in-plane Young's modulus of [0/90] single layer, the E1 and E2 of the [45/-45] single layer are much smaller. This is due to less fibres existing in this direction. In addition, the Poisson's ratio are different, compared with the [0/90] single layer. The Poisson's ratios  $\nu 12$  and  $\nu 21$  are over 0.76. It is noticeable that they are increasing with an increasing multi-scale void percentage, although the increasing values are not too big.

In Table 4.5, some specific data is listed for analysis. All the Young's modulus have a decline over 11% when the multi-scale voids increase to 5%. This is because fibres are not absolute dominant anymore in this direction. Although there are some fibres working, the decreasing percentages of the Young's modulus are close to the decreasing percentage of the resin system in Table 3.5. Different from other material properties, the Poisson's ratios  $\nu 12$  and  $\nu 21$  are larger than 0.5 and increase with an increasing void percentage. The increasing percentages are around 3% when the void percentage is up to 5%. For the other Poisson's ratio, although the values are smaller than 0.1, the decreasing percentages are all larger than 12%.

macro and micro voids	0.5%	5%
E1(MPa)	1.62%	11.79%
E2(MPa)	1.62%	11.77%
E3(MPa)	2.57%	15.17%
G12(MPa)	0.25%	1.67%
G13(MPa)	1.95%	13.59%
G23(MPa)	1.97%	13.67%
v12	-0.39%	-3.02%
v21	-0.39%	-3.03%
v13	2.16%	12.45%
v31	3.11%	15.81%
v23	2.17%	12.46%
v32	3.11%	15.83%

**Table 4.5:** Material properties decreasing percentages for [45/-45] single layer, where both micro and macro voids increase to 0.5%, 5%.

#### 4.2.3 [0/90] Single Layer vs. [45/-45] Single Layer

Comparing the [0/90] and [45/-45] single layer, the Young's modulus E1 and E2 of the [0/90] single layer are almost four times of these of the [45/-45] single layer, show in Figure 4.7 and Figure 4.8. However, the decreasing percentages of the E1 and E2 of the [0/90] single layer are much smaller than these of the [45/-45] single layer, shown in Table 4.4 and Table 4.5. Compared with the [0/90] single layer, the [45/-45] single layer has less fibres dominant. The decreasing percentage is close to that of the pure resin system. The decreasing percentages of Young's modulus E3 of these two layers are similar, around 15%, when the void percentage increases to 5%. For both single layers, E3 is close to 9GPa when the layer does not have any voids. No matter which layer, in the out-of-plane direction, the resin is dominant instead of fibres. Therefore, E3 of the layer is close to the Young's modulus of the resin system in Table 3.5.

For Poisson's ratio,  $\nu 12$  and  $\nu 21$  are totally different for the [0/90] and [45/-45] single layers. They are less than 0.05 for the [0/90] single layer and experience a decline with an increasing void percentage. However, for the [45/-45] single layers, the values are up to 0.76 and have a growth with an increasing void percentage.

## 4.3 Macro Mechanical Properties

In this section, there are two kinds of laminates included to analyze the effect of the multi-scale void percentages on mechanical properties at macro scale. One of them is the thick laminate with the same void percentages everywhere, described in Section 4.3.1. In this laminate, the void percentage for micro and micro voids are the same for each node. It is not related to a specific location, which means multi-scale voids are evenly distributed in the laminates. The purpose of this subsection is to understand the effect of void percentages on the mechanical properties of the laminates. The other one discussed in Section 4.3.2 includes the influence of

	case 1	case 2		case 3		case 4	
$\operatorname{void}(\%)$	0	0.5	$\downarrow$	2	$\downarrow$	5	$\downarrow$
E1(MPa)	48756	48571	0.379%	48206	1.128%	47464	2.650%
E2(MPa)	48401	48259	0.293%	47894	1.047%	47146	2.593%
E3(MPa)	8688	8449	2.751%	8247	5.068%	7368	15.195%
G12(MPa)	14294	14242	0.364%	14086	1.455%	13759	3.743%
G23(MPa)	2860	2779	2.814%	2665	6.842%	2453	14.254%
G13(MPa)	2841	2799	1.471%	2684	5.544%	2470	13.069%
$\mathbf{v12}$	0.248	0.248	-0.081%	0.249	-0.363%	0.250	-0.888%
$\mathbf{v21}$	0.246	0.246	-0.163%	0.247	-0.447%	0.248	-0.935%
v13	0.282	0.282	0.425%	0.280	0.708%	0.276	2.266%
v31	0.050	0.049	1.988%	0.049	3.180%	0.043	14.911%
v23	0.291	0.283	2.613%	0.284	2.339%	0.276	5.158%
v32	0.052	0.050	4.981%	0.049	6.322%	0.043	17.433%

**Table 4.6:** Mechanical properties of the thick laminate with certain multi-scale void percentage in macro scale.

the location of multi-scale voids and various void percentages of micro and macro voids. The purpose of this subsection is to figure out if the effect of void percentage on the mechanical properties of the laminate would change with an increasing thickness.

#### 4.3.1 Mechanical Properties of the Thick Laminate with Even Multi-scale Void Percentage in Macro Scale

The layup of the whole laminate is  $[(45/-45)_2(0/90)_3]_{20s}$ . In this section, it is assumed that all the layers in the laminate have the same multi-scale void percentages. There are 4 cases listed in Table 4.6. For example, for case 1, there are 40% [45/-45] single layers and 60% [0/90] single layers. All of them have the macro- and micro-void percentage 0%. Similarly, for case 2, the percentage is 0.5%.

The in-plane Young's modulus E1 and E2 are similar, around 48.5GPa. If there are more [45/-45] layers, the in-plane Young's modulus would be lower. With an increasing void percentage, the in-plane Young's modulus would have a 2.650% reduction when the multi-scale void percentage is up to 5%. Compared with the variation of E3, the decreasing percentages of E1 and E2 are small. This is because of the in-plane fibres which can hold more loads and are not affected by voids. However, the out-of-plane E3 has a large reduction due to the multi-scale voids. It reduces more than 15% when the multi-scale void percentage increases to 5%.

Similar consequences are shown for the Shear modulus. The in-plane Shear modulus G12 has a small reduction, around 3.7%. The out-of-plane Shear modulus G13 and G23 experience a lager decline, and the rates are 13.069% and 14.254%, respectively.

For the Poisson ratio, although there are only 40% [45/-45] layers, the  $\nu 12$  and  $\nu 21$  of the thick laminates have the similar uptrend with these of the [45/-45] single layer with an increasing void percentage. However, compared with the [45/-45] single layer, the uptrend of the thick

	20 mm thick laminate			40 mm thick laminate			
	injection injection injection		injection	injection	injection		
	strategy 1	strategy 2	strategy 3	strategy 1	strategy 2	strategy 3	
E1	48616	48608	48609	48612	48610	48610	
E2	48297	48289	48291	48293	48293	48291	
E3	8531	8531	8523	8526	8526	8526	
G12	14244	14242	14242	14243	14242	14242	
G23	2824	2822	2822	2823	2822	2822	
G13	2819	2803	2806	2808	2803	2803	
V12	2819	2803	2806	2808	2803	2803	
V21	0.248	0.246	0.246	0.246	0.246	0.246	
V13	0.283	0.282	0.283	0.283	0.283	0.283	
V31	0.050	0.050	0.050	0.050	0.050	0.050	
V23	0.283	0.283	0.283	0.283	0.283	0.283	
V32	0.050	0.050	0.050	0.050	0.050	0.050	

 Table 4.7: Mechanical properties of the thick laminate with various multi-scale void percentages and locations in macro scale.

laminate is smaller, around 1% when the void percentage increases to 5%. For the other Poisson's ratios, they all reduce with an increasing void percentage.

Overall, most of the material properties (excluding  $\nu 12$  and  $\nu 21$ ) reduce due to an increasing multi-scale void percentage.

#### 4.3.2 Mechanical Properties of the Thick Laminate with Various Multi-scale Void Percentage and Void Location in Macro Scale

In this subsection, there are 6 cases included to analyze the effect of various void percentages and void locations on the mechanical properties in terms of an increasing thickness at macro scale. The fibre volume is 55%, the filling temperature is 100°, and the injection pressure is 4 bar. The permeabilities  $\kappa_{11}$ ,  $\kappa_{22}$ , and  $\kappa_{33}$  are  $1.5 \times 10^{-11} m^2$ ,  $1.25 \times 10^{-11} m^2$ , and  $1.25 \times 10^{-13} m^2$ . respectively. There are two thicknesses 20mm and 40mm considered. Also three different injection strategies are included. Specific data is shown in Table 4.7.

With an increasing laminate thickness, the material properties are nearly the same, even if injection strategy changes. This is because the average multi-scale void percentage is nearly constant for these laminates. More than half of the elements of these laminates have the macro-void percentage close to 0.35%. And more than 75% of the elements of these laminates have the micro-void percentage close to 0.2%. This means that even if the laminate thickness increases, most of the material properties per layer are following these of the single layer with 0.35% macro voids and 0.2% macro voids. After all, when calculating the laminate properties at macro scale, the material properties do not change with an increasing thickness. Besides, all of these laminates have the material properties in between case 1 and case 2 in Table 4.6. This is because all the elements in these 6 laminates have the macro-void percentage in the range of 0 - 0.5%.

Overall, the material properties do not reduce due to an increasing thickness.

## 4.4 Validation

Above FEM simulation solution will be verified with data from literature [68] in this section.

Hongyan experimentally investigated the effect of the void content on the tensile modulus of  $[(45/-45)_4/(0/90)/(45/-45)_2]_s$  (A) and  $[(45/-45)/0_4/(45/-45)(0/90)]_s$  (B) T300/914 prepreg fabric composites. The specimens have voids in the range of 0.4% to 9.0%. The fibre content of the prepreg was 58% - 62%. The longitudinal tensile modulus of the laminate B is not influenced by the void content, shown in the Figure 4.9. This is because the laminate B has four 0-degree layers. The fibres in this direction can carry much tensile load and the effect of voids on the resin do not have too much effect on them. However, for the laminate B, the tensile modulus is sensitive to the void content. It decreases by 14% when the void content up to 8%, show in Figure 4.9.

For the validation simulation, the material properties of the T300 carbon fibre are listed in Table 3.6. The density of the 914 Hexcel <sup>®</sup> HexPly <sup>®</sup> 914 175° Curing Epoxy Matrix is 1.29 g/cc [69]. The tensile modulus is 3.90 GPa and the Poisson's ratio is 0.41. The fibre content is limited into 58%. For the validation of laminate A, the tensile modulus loss matches well when the void content increases to 6%. Both of the validation A and the experimental laminate A from literature have a 10% reduction. For the validation B, the decreasing rate of the validation B is larger than that of the literature, 5% and 3% respectively, but it is still within the test data scatter.

Therefore, this FEM simulation solution is reliable to predict the properties loss of the fabric composite as a function of the void content.



**Figure 4.7:** Material properties of the [0/90] single layer with the micro and macro voids.



Figure 4.8: Material properties of the [45/-45] layer with the micro and macro voids.



Figure 4.9: Tensile modulus fraction as a function of void content.

# Chapter 5

# **Conclusions, and Recommendations**

## 5.1 Research Overview and Conclusions

The start point of this thesis was to predict void percentages and locations caused by RTM filling process and to simulate their effect on the mechanical properties of thick laminates. The main work in above chapters is summarized:

- 1. The literature study was summarized in Chapter 2. Equation 2.3 implied which parameters have effect on the void parentage and proved by Chapter 3. This chapter finished the step 1 mentioned in Section 1.2.
- 2. In Chapter 3, the solution of predicting the multi-scale void percentages and locations caused by the filling process and their effect on the stiffness was developed. The method was based on the FEM analysis by using the commercial software PAM-RTM, Digimat, and ABAQUS. This chapter finished step 2 mentioned in Section 1.2.
- 3. In Chapter 4, the simulation results were presented and discussed. First was the filling process simulation. Some parameters that have influence on the multi-scale void percentage were summarized. The meso-scale RVEs simulation results were then shown. Next was the stiffness simulation of the thick laminate at macro scale. Finally, verification with data from literature was introduced and the results matched well. This chapter finished step 3 and 4 mentioned in Section 1.2.

From the above steps the following can be concluded:

- 1. The average multi-scale void percentage does not change due to the increasing thickness.
- 2. The micro-void percentage has a slight change with various variables, which can be ignored. The change in the macro-void percentages is complex due to the different variables in different injection strategies and are listed in Table 5.1.

	fibre volume	Injection pressure	Permeability $\kappa_{11}$	Permeability $\kappa_{33}$	Filling temperature
Injection strategy 1	×	large	large	×	×
Injection strategy 2	×	$\operatorname{slight}$	×	×	×
Injection strategy 3	×	$\mathbf{moderate}$	$\operatorname{slight}$	$\operatorname{slight}$	×

**Table 5.1:** The influence of variables on the macro-void percentage (no influence  $\times$ ).

**Table 5.2:** The influence of multi-scale void percentage on material properties of [0/90] single layer and [45/-45] single layer (reduction  $\downarrow$ , increase  $\uparrow$ , no influence  $\times$ ).

	[0/90]	[45/-45]		[0/90]	[45/-45]
E1(GPa)	×	$\downarrow$	v12	×	$\uparrow$
E2(GPa)	×	$\downarrow$	v21	×	$\uparrow$
E3(GPa)	$\downarrow$	×	v13	×	$\downarrow$
G12(GPa)	$\downarrow$	$\downarrow$	v31	$\downarrow$	$\downarrow$
G13(GPa)	$\downarrow$	$\downarrow$	v23	×	$\downarrow$
G23(GPa)	$\downarrow$	$\downarrow$	v32	$\downarrow$	$\downarrow$

- 3. Most of the material properties of the [0/90] and [45/-45] single layer reduce due to multi-scale voids, shown in Table 5.2. The in-plane material properties of the [0/90] single layer have a less reduction due to the existing multi-scale voids as fibres instead of the resin are dominant in this direction. Fibres are soft because of voids and all the voids are in the resin system. The Poisson's ratios  $\nu 12$  and  $\nu 21$  are quite large, around 0.76. And they increase with the increasing void percentage.
- 4. Most of the material properties (exclude  $\nu 12$  and  $\nu 21$ ) reduce due to an increasing multi-scale void percentage. The material properties do not reduce due to the increasing thickness.

## 5.2 Recommendations

For deeper understanding the effect of defects on mechanical properties of composite laminates due to the increasing thickness, future work could include the following points:

- 1. In order to achieve more accurate results that are comparable with the experimental data, it is better to measure the permeablities, fibre volume, void content as a function of the capillary number and to use in both simulations and validation experiments.
- 2. No matter which defects, it is processes induced. It is better to experimentally monitor their formation, locations, and sizes and then to calibrate the prediction results.
- 3. When including the void defects, the matrix-dominated properties experience a decline with an increasing void percentage. This implies that when using thick composite laminates, it is better to use 3D woven, if the laminate mainly needs to carry out-of-plane loads.

4. The effect of more defects (i.e., residual stress and fibre misalignment) on the mechanical properties due to the growing thickness can be included. A short literature review on the defect formation and simulation methods are listed in the Appendix A and Appendix B.

Conclusions, and Recommendations
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## Appendix A

### **Residual Stress**

After the filling process, the resin system with the fabric will be cured for certain hours at high temperature. The conventional curing cycle is not suitable for thick FRPCs. In [4], experimental evaluation shows the distributions of temperature and degree of curing in thick laminates. The temperature difference though the thickness and the maximum temperature are rising with increasing thickness, shown in Figure A.1. When the thickness increases from 1mm to 84mm, the monitored temperature goes up from 40 degree to 80 degree. The heat energy is not easily conducted through the resin system due to its poor thermal conductivity. When the heat energy from the exothermic reaction is accumulated too much, it would lead to a degeneration of the laminate properties. The overshooting and the different thermochemical properties of the resin and the fabric contribute the residual stresses during this process. Warpage, delamination and matrix-cracking are the consequences of the residual stress.



Figure A.1: Temperature distribution in 85mm laminate [4]

Researchers [70,71] developed numerical curing models from initial heat conduction equation based on chemical kinetics  $\left(\frac{d\alpha}{dt}\right)$  of resin. The heat conduction boundary conditions include the thermo-chemical-mechanical effect [72]. The degree of curing  $\alpha$  in each time step  $\Delta t$ is based on the previous step and the instantaneous curing rate (chemical kinetics). The thickness effect is discussed in [71] and it proved that it is valuable to set more dwell for increasing cured area and reducing the residual stresses in thick laminates.

$$\alpha_{i,j}^{t+\Delta t} = \alpha_{i,j}^t + \left(\frac{d\alpha}{dt}\right)_{i,j}^t \Delta t \tag{A.1}$$

The chemical kinetics, mentioned in last paragraph, is the degree of curing depending on temperature history. The expression could be first-, second-, (shown below [73]) or even third order [74] as a function of degree of curing and its corresponding Arrenius relationship with temperature. The order of the function is the order of reaction with respect to a given substance. This relation is analysed by Xiaogang Huang and John [73] based on autoclave process and DSC empirical data (the coefficients  $A_1$ ,  $A_2$ , the increment modules  $\Delta E_1$ ,  $\Delta E_2$ ).

$$\frac{d\alpha}{dt} = (k_1 + k_2 \cdot \alpha^m) \left(\alpha_{max} - \alpha\right)^n \tag{A.2}$$

$$k_1 = A_1 exp\left(\frac{-\Delta E_1}{RT}\right) \tag{A.3}$$

$$k_2 = A_2 exp\left(\frac{-\Delta E_2}{RT}\right) \tag{A.4}$$

The parameters R and T are the gas constant and temperature, respectively.

Like the increment modules in above equations, the composite elastic modulus  $E^{1,2}_{comp}$ , a function of temperature T and fiber volume  $V_f$ , can be described by an empirical model [75].

$$E_{composite}^{1,2} = \left(\frac{V_f\left(E_f^i - E_R\left(T,\alpha\right)\right)}{1 + A_i \cdot exp\left(B_i \cdot T\right)} + E_{AGP}\left(T\right)\right) \left(\frac{E_r\left(T,\alpha\right)}{E_r\left(T,1\right)}\right)$$
(A.5)

where i=1,2 is two normal fiber directions, and  $A_i$ ,  $B_i$  are constant coefficients.  $E_r$  is the modulus of the resin, and  $E_{AGP}$  is the modulus of resin at gel point. It was found that after gel point, the elastic modulus is very low as the degree of polymerization is less than 40% [75]. Thus, following mechanical analysis is based on higher polymerization levels.

With varied elastic modulus of composite  $E_{comp}^{1,2}$ , the stiffness matrix  $[C_{ij}]$  of the composite laminates (also depends on the degree of curing and temperature) needs iteration computation. Further, the strain-stress  $(\sigma_j - \varepsilon_j)$  modeling [75] is developed in an infinitesimal small region based on Classical Laminated Theory (CLT).

$$\{\sigma_j\}_t = \int_{t(AGP)}^t [C_{ij}]_t \left\{\frac{\partial \varepsilon_j}{\partial t}\right\} dt, for j = 1 - Npiles$$
(A.6)

where the strains  $\varepsilon_j$  is the consequence of chemical-induced shrinkage  $(\varepsilon_{sh})$  and thermalinduced strains  $(\varepsilon_{th})$  [73,74,76].

For solving the problem more efficiently, computer technology is introduced to reduce the computational effort. COMSOL  $Multiphysics^{TM}$  [77] and PAM-Distortion have a visual result of the degree of curing distributions at different curing temperature and time. PAM-Distortion also shows the possibility of the prediction of the deformed geometries, like spring

back and warpage. By adding suitable subroutines, ABAQUS [73, 76, 78] could combine the thermo-chemical-mechanical effect to simulate the degree of curing and the process-induced strain over process.

For this process-induced residual stress (strain), the Fiber Bragg Grating (FBG) sensing technique is developed to monitor its formation, which has a high precision and sensitivity. By embedding FBG sensors in specimens, the matrix shrinkage contributing the residual stress formation is investigated [26,79]. Michaud [78] used heat flux sensors (HFSs) to measure the internal curing behavior for 25.4mm thick composite laminates, which is an effective means of feedback for control purposes. However, it is limited when there are two conflicting heat transfer driving forces.

# Appendix B

### **Fibre Misalignment**



**Figure B.1:** schematic diagram of defects: deformed plies (waviness), interface crack, rich resin region [10]

The rich resin and the local fibre deformation (waviness) are frequently encountered in thick FRPCs, leading to fiber misalignments, shown in Figure B.1. Rich resin area is an accumulation of the pressure gradient, which washes fibers out-of-line during the filling process. The misalignment tendency increases because of the residual stresses built up during the curing process in thicker laminates [13]. In autoclave and filament winding processes [13, 80], it is clear that this tendency has an impact on the mechanical properties under compressive loading. RTM would intensify this effect due to the additional filling process, shown in Table B.1. The deviations of fibre orientation of RTM are larger than that of pre-preg in both out-of-plane and in-plane direction. These defects combining interface cracks cause a substantial dropping of Young's modulus and strength under compressive loading [10]. [81] experimental results demonstrate the specimen with such defects have a 25% strength drop.

There are three waviness models [13]. Each of them has their own amplitude and wavelength, which derives different transformed compliances shown in Table B.2. In ABD matrix of composite, stiffness components  $Q_{ij}$  (i,j=x,y) in equation B.1, are rotated from the coordinate system of material direction to global coordinate system [82]. Because of the fibre

Manufacturing	Waviness plane	Correlation length in longitudinal direction (mm)	Correlation length in transverse direction (mm)	Deviation of fiber orientation (degree)
RTM	Out of plane	0.77	0.46	1.63
	In plane	0.84	0.35	1.37
Pre-preg	Out of plane	1.23	0.5	0.67
	In plane	1.04	0.3	1.12

Table B.1: Waviness information in RTM and Pre-preg [12]

Table B.2: Different scales in fabric and corresponding flow characteristics [13]

model	properties	Equation of amplitude and wavelength
Uniform fiber waviness model	ds ds dx off-Axis z y th h	$ \theta_l = \tan^{-1} \left( \frac{2\pi a_l}{\lambda_l} \cos\left( \frac{2\pi x}{\lambda_l} \right) \right) $
Graded fiber waviness model	Thin Slice Element	$\theta_{l} = \tan^{-1} \left( \frac{2\pi a_{l}(z_{l})}{\lambda_{l}} \cos\left(\frac{2\pi x}{\lambda_{l}}\right) \right)$ $a_{l} = a_{0} \left( 1 - \frac{2 z_{l} }{h \cdot V_{ct}} \right) \left( 1 - u \left( ( z_{l}  - \frac{h \cdot V_{ct}}{2}) \right) \right)$
Localized fiber waviness model	h hw L	/

misalignment, the related angle  $\theta$  is necessary to be modified by the equation in Table B.2 with respect of the waviness models. The average transformed compliance  $\bar{S}_{ij}$  usually is used for next derivation of Young's modulus and Position's ratio [13,80]

$$\begin{aligned} Q_{xx} &= m^{4} \cdot Q_{11} + n^{4} \cdot Q_{22} + 2 \cdot m^{2} \cdot n^{2} \cdot Q_{12} + 4 \cdot m^{2} \cdot n^{2} \cdot Q_{66} \\ Q_{yy} &= n^{4} \cdot Q_{11} + m^{4} \cdot Q_{22} + 2 \cdot m^{2} \cdot n^{2} \cdot Q_{12} + 4 \cdot m^{2} \cdot n^{2} \cdot Q_{66} \\ Q_{xy} &= m^{2} \cdot n^{2} \cdot Q_{11} + m^{2} \cdot n^{2} \cdot Q_{22} + \left(m^{4} + n^{4}\right) Q_{12} - 4 \cdot m^{2} \cdot n^{2} \cdot Q_{66} \\ Q_{xs} &= m^{3} \cdot n \cdot Q_{11} - m \cdot n^{3} \cdot Q_{22} + (m \cdot n^{3} - m^{3} \cdot n) Q_{12} + 2 \left(m^{3} \cdot n - m \cdot n^{3}\right) Q_{66} \end{aligned} \tag{B.1}$$

$$\begin{aligned} Q_{ys} &= m \cdot n^{3} \cdot Q_{11} - m^{3} \cdot n \cdot Q_{22} + (m^{3} \cdot n - m \cdot n^{3}) \cdot Q_{12} + 2 \cdot (m \cdot n^{3} - m^{3} \cdot n) \cdot Q_{66} \\ Q_{xy} &= m^{2} \cdot n^{2} \cdot Q_{11} + m^{2} \cdot n^{2} \cdot Q_{22} - 2 \cdot m^{2} \cdot n^{2} \cdot Q_{12} + \left(m^{2} - n^{2}\right)^{2} \cdot Q_{12} \\ m &= \cos\theta, n = \sin\theta \end{aligned}$$

In [83], random waviness with equal wavelength and amplitude is implemented in the model. Using the Monte Carlo method, the compressive strength shows a drop with the misalignment angle changing from 2° to 10°. Based on the continuum theory, Norman [84] calculated the decreasing compressive strength with waviness shape changing. Sutcliffe [85] predicted a significant strength reduction with increasing waviness amplitude in random waviness distributions using the ABAQUS and Matlab subroutine. It is more accurate to set the location and size of waviness based on experiments instead of random distribution. In [86], the non-linear, inter-laminate, stress-strain relation obtained by DIC technique was implemented in ABAQUS. By subroutine USDFLD, the failure load for waviness coupons and delamination were predicted and observed. These predictions show a modest reduction in strength with increasing waviness size and the results are sensitive to the assumed waviness distribution.

More experiment results show a reduction of mechanical properties with waviness in different thick laminates. Chun [13] experimentally obtained compressive/tensile stress-strain curves in three waviness models. The 4.32mm thick specimens [10] with 29 degrees out-of-plane waviness or 30 degree in-plane waviness have the 71.5% and 35% reduction of compressive strength, respectively. Hsiao [80,87] used 9mm, 9.14mm, and 19.05mm thick laminates and gained the stress-strain curves under compressive loading. When the ratio of the amplitude to the wavelength increases from 0 to 0.2, the major Young's modulus of the localized waviness model, graded waviness model, and uniform waviness model reduce around 15%, 80%,90%, respectively.

The Digital Image Correlation (DIC) technique [86] using correlation full-field strain measurement can put the generated geometry and location information of waviness into ABAQUS for mechanical analysis, which accurately builds a FE model with the waviness defects. Computed tomography (CT) [88,89] is able to measure both waviness and voids in thick FRPCs. In [12], the Multiple Field Image Analysis (MFIA) technique for 2D RTM and the X-ray CT technique for 3D prepreg are used to collect the waviness information. However, the maximum X-ray energy is too low for penetration of thick composite parts [88].