Optimizing Vacuum Assisted Resin Transfer Moulding (VARTM) Processing Parameters to Improve Part Quality

by

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Abstract

The Low Cost Composites (LCC) group at Carleton University is studying out-of-autoclave composite manufacturing processes such as Vacuum Assisted Resin Transfer Moulding (VARTM) and Closed Cavity Bag Moulding (CCBM). These processes are used to produce inexpensive and high performance components for the GeoSurv II, an Unmanned Aerial Vehicle (UAV) being developed at Carleton University. This research has focused on optimizing VARTM processing parameters to reduce the weight and improve the strength and surface finish of GeoSurv II composite components.

A simulation was developed to model resin flow through in VARTM infusions and was used to simulate mould filling and resin emptying of the GeoSurv II inverted V-empennage and mission avionics hatch. The resin infusion schemes of these parts were designed to ensure full preform resin saturation, and minimize thickness variations.

An experimental study of the effects of the presence of a corner on composite thickness, void content, and strength was conducted. It was found that inside corners result in local increases in thickness and void content due to poor preform compaction. A novel bagging technique was developed to improve corner compaction, and this technique was shown to reduce thickness variability and void content. The strength, void content, and thickness variation were found to be heavily dependent on corner radius, with corner radii greater than 6.4 mm displaying the greatest improvement in performance for the layups considered. The design of the empennage and hatch mould incorporated the results of this study to improve the quality of these components.

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List of Acronyms

ASTM - American Society for Testing and Materials
CCBM - Closed Cavity Bag Moulding
DAQ - Data Acquisition
FSR - Force Sensing Resistor
GUI - Graphical User Interface
LCC - Low Cost Composites
LCM - Liquid Composite Moulding
LIMS - Liquid Injection Moulding Simulation
MDF - Medium Density Fibre
MTS - Material Test System
PDE - Partial Differential Equation
RTM - Resin Transfer Moulding
S-RIM - Structural Reaction Injection Moulding
UAV - Unmanned Aerial Vehicle
VARI - Vacuum Assisted Resin Infusions
VARTM - Vacuum Assisted Resin Transfer Moulding

List of Symbols

A - Area [m^2]

A_1 - Permeability coefficient [m^2]

B - Compaction exponent

b_1 - Permeability exponent

CBS - Curved beam strength [$\text{N}\cdot\text{m}/\text{m}$]

d - Thickness increase to be added to servo mounting plate opening [m]

D - Diameter of cylindrical rollers [m]

d_x - Horizontal separation of top and bottom cylinders [m]

d_y - Vertical distance between cylindrical loading bars [m]

E_f, E_m - Stiffness of fibre and matrix, respectively [Pa]

E_r, E_θ - Stiffness in radial and tangential directions, respectively [Pa]

F - Applied load [N]

h - Local material thickness [m]

K - Permeability [m^2]

k - Kozeny constant

k_0 - Modified Kozeny constant [m^2]

k_∞ - Kinetic analogue of μ_∞ [$1/\text{s}$]

K' - Modified LIMS permeability [m^2]

M - Applied moment [$\text{N}\cdot\text{m}$]

N - Ply count
 P - Pressure [Pa]
 Q - Volume flow rate [m³/s]
 R - Universal gas constant [J/mol·K]
 r_i - Inner radius of test specimen [m]
 r_o - Outer radius of test specimen [m]
 s - Fibre specific surface [1/m]
 S_d - Fibre area weight [kg/m²]
 SD_{2ply} - Standard deviation of flat section thickness for 2-ply layup [m]
 T - Temperature [K]
 t - Time [s]
 t_{max} - Maximum thickness of preform [m]
 t_s - Specimen thickness [m]
 u - Darcy velocity [m/s]
 v - Interstitial resin velocity [m/s]
 v_f - Fibre volume fraction
 v_{f0} - Fibre volume fraction at 1 Pa
 w - Specimen width [m]
 α - Viscosity cure exponent 1
 β - Viscosity cure exponent 2 [1/s]
 Δ - Vertical deflection of test specimen at failure [m]
 ΔE_k - Kinetic analogue of ΔE_μ [J/mol]
 ΔE_μ - Arrhenius activation energy for viscosity [J/mol]
 μ - Viscosity [Pa·s]
 μ - Initial viscosity [Pa·s]
 μ_∞ - Infinite temperature reference viscosity [Pa·s]
 ϕ - Half the overall angle between specimen loading arms

ϕ_i -Initial value of ϕ with no deflection

ρ - Density [kg/m³]

σ - Standard deviation

σ_r - Interlaminar strength [Pa]

Chapter 1

Introduction

Unmanned Aerial Vehicle (UAV) technology has been used by the military for a number of years for surveillance and combat roles, and has traditionally come with a large price tag. Recently, advances in low-cost UAV technology such as open source autopilots and inexpensive sensors have allowed the use of UAVs to expand to new civilian markets. UAV technology is currently being used in the energy sector, agriculture industry, and resource exploration industry, as well as many other commercial applications [1]. Between 2005 and 2011, the number of UAV producers has more than doubled, which was mostly driven by an expanding civilian UAV market [2].

Researchers at Carleton University are developing a UAV called the GeoSurv II in collaboration with Sanders Geophysics Limited (SGL) to perform mineral exploration surveys using an airborne magnetometer system. The GeoSurv II is a proof-of-concept model and testing platform designed to demonstrate that geo-magnetic surveys can be done by a UAV for less cost than manned aerial surveys, without putting a human pilot at risk.

The cost of manufacturing the GeoSurv II must be kept as low as possible if it is to be an economically feasible aeromagnetic survey tool. The Low-Cost Composites (LCC) group at Carleton University has been mandated to develop an inexpensive composites manufacturing technique tailored to the requirements of the GeoSurv II

UAV. Maley [3] and Mahendran [4], two LCC researchers at Carleton, developed a novel method of inexpensively forming complex composite sandwich structures using the Vacuum Assisted Resin Transfer Moulding (VARTM) process. This method has been successfully used to manufacture the GeoSurv II fuselage.

This research built on the work of Maley and Mahendran, and was focused on optimizing VARTM processing parameters to improve the quality of the parts that are produced. A simulation tool was developed to minimize thickness variations and prevent dry spot formation within VARTM lamina, and the effects of various processing parameters on the dimensional tolerances, void content, and strength of complex three-dimensional parts were investigated. The results of this research were used to optimize the manufacturing process of the GeoSurv II empennage and mission avionics hatch.

1.1 GeoSurv II Unmanned Aerial Vehicle (UAV)

The GeoSurv II is a test platform used for the development of a UAV capable of performing magnetic total field and gradiometer surveys. The GeoSurv II must be able to operate in diverse geographical areas and will not necessarily have access to prepared landing strips. Sample specifications for the GeoSurv II are listed in Table 1 [5].

Table 1: Specifications of the GeoSurv II UAV

Wing span	4.9 m
Maximum takeoff weight	75 kg
Cruise speed	30-50 m/s
Power plant	16.4 kW gasoline engine in pusher configuration
Flight time	2 hours

Figure 1 shows the GeoSurv II prototype, as manufactured by the 2009/10 UAV Project Team. It should be noted that this design contains a "U" empennage, and has large aluminum landing gear.

Figure 1: GeoSurv II prototype (February 2010) [4]

Fourth year engineering students on the 2012/13 GeoSurv II Project designed new inverted V-empennage, shortened the length of the tail booms, and constructed smaller composite landing gear. These modifications allowed the maximum takeoff mass of the GeoSurv II UAV to be reduced from 109 kg to 75 kg. The new GeoSurv

II design is shown in Figure 2.

Figure 2: Improved GeoSurv II design (May 2013)

These design changes have necessitated the manufacturing of several new GeoSurv II components. The aim of this research was to optimize the VARTM process to manufacture two of these components: the inverted V-empennage, and the mission avionics hatch mounted to the underside of the fuselage.

1.2 Thesis Organization

This thesis is organized into the following chapters:

- **Chapter 2:** Common composite manufacturing methods are discussed. An overview of four Liquid Composite Moulding (LCM) processes is given. Manufacturing defects that have been encountered while manufacturing GeoSurv II components are described.

- **Chapter 3:** Four options for flow simulation software are discussed. A weighted trade-off study is used to select two software solutions to simulate resin flow in the VARTM process.
- **Chapter 4:** Darcy's law is used to derive equations of resin flow. The compaction behavior and permeability of carbon fibre layups is measured. The viscosity of the resin is characterized during cure. Algorithms are developed to simulate mould filling and resin emptying in a VARTM infusion.
- **Chapter 5:** An experimental method is used to determine the effects of the presence of a corner in composite lamina on thickness, void content, and strength. A novel bagging method is described that makes use of highly flexible vacuum bagging material combined with silicone pressure enhancers. Both inside and outside corners of different radii are tested for both the novel bagging technique, and the technique that has been used by previous LCC researchers.
- **Chapter 6:** The simulations developed in Chapter 4 and the experimental study of corner quality developed in Chapter 5 are used to optimize the manufacturing procedure of the GeoSurv II mission avionics hatch and inverted V-empennage.
- **Chapter 7:** Conclusions that were drawn from this research are presented, as well as recommendations for future work.

1.3 Contributions

In this research, a VARTM infusion simulation was developed. The simulation was used to optimize the placement of inlets and outlets in the infusion of the mission avionics hatch to prevent dry spot formation. A novel technique was developed to

estimate the permeability of a fibrous preform over a range of fibre volume fractions using only a single experiment.

Frequently, a vacuum pump is used to remove excess resin from VARTM parts after infusion. A model was developed to predict the resin emptying behaviour during this stage, and was used to optimize the CCBM process used to manufacture the inverted V-empennage. A resin distribution channel spacing was selected using this simulation to minimize thickness variations.

Experiments were conducted to quantify the defects that are found in complex three-dimensional composite structures. A method to measure compaction pressure underneath the vacuum bag was developed and used to show that fibre compaction pressure is low in the vicinity of corner defects. The effects of the presence of inside and outside corners of different radii on thickness variations, void content, and strength were measured for parts made using the CCBM process, as well as for a novel manufacturing process.

This thesis has contributed to the understanding of resin flow in VARTM infusions, particularly as it relates to resin emptying. Furthermore, contributions were made to understanding and quantifying common defects found in complex three-dimensional composite components. Novel strategies were developed to reduce thickness variations within VARTM components and a strategy was developed to mitigate corner defects.

Chapter 2

Composite manufacturing techniques and common manufacturing defects

The processes that are used to manufacture composite structures are numerous and diverse, and will produce parts with a wide range of cost and quality. All composite manufacturing methods incorporate a technique to form a porous reinforcement to a desired shape and infiltrate it with a matrix material. However, each process accomplishes these two steps using widely differing techniques. A wet layup is the simplest and least expensive process, but produces parts of low quality. Autoclave manufacturing is extremely expensive and requires large equipment, but produces high quality parts. A family of processes referred to as Liquid Composite Moulding (LCM) sit between wet layup and autoclave processes; LCM processes cost much less than autoclave manufacturing, and are able to produce parts of a higher quality than those made using a wet layup. However, the cost of LCM processes is greater than that of a wet layup, and the part quality is lower than autoclave parts.

Autoclave processes have not been considered by LCC researchers as a feasible method to manufacture GeoSurv II components. The cost required to operate an autoclave is beyond the budget of this project, and does not fit with the research goals of the Low Cost Composite (LCC) group. For this reason, composite autoclave

manufacturing is not discussed further, but information on this family of processes can be found in [6–8].

Maley [3] compared several different out-of-autoclave composite forming processes, and determined that a LCM process known as Vacuum Assisted Resin Transfer Moulding (VARTM) provides the best combination of part quality and low cost for the GeoSurv II aircraft. Maley also developed the Moldless VARTM method, which can be used to manufacture large, complex sandwich structures in a single step. Mahendran [4] built upon this technique, and developed the Closed Cavity Bag Moulding (CCBM) process which he used to manufacture two fuselages for the GeoSurv II.

This chapter provides an overview of some commonly used LCM processes, including the mouldless VARTM method developed by Maley [3], and the CCBM method developed by Mahendran [4]. Various parameters that characterize the quality of composite parts are discussed and some common defects that have been encountered by researchers at Carleton University are studied.

2.1 Overview of select Liquid Composite Moulding (LCM) processes

LCM processes involve the saturation of a fibrous bed with a liquid resin, which is then allowed to gel to form a composite part. The saturation process is referred to as an infusion. In general, the shape of the part is formed using a mould or moulds, and fluid motion is achieved by pressurizing the resin, pulling vacuum in the preform, or a combination of both. Many different variants of the LCM process have been developed, including Resin Transfer Moulding (RTM), Light RTM, Vacuum Assisted Resin Transfer Moulding (VARTM), and Structural Reaction Injection Moulding (SRIM), each with its own unique set of advantages and disadvantages [8].

The following sections describe RTM and VARTM, two common LCM processes, as well as Mouldless VARTM and Closed Cavity Bag Moulding (CCBM), two variants of VARTM that have been developed at Carleton University.

2.1.1 Resin Transfer Moulding (RTM)

Resin Transfer Moulding (RTM) is a type of LCM process that uses a two-sided matched mould to form composite parts. The preform is compressed between the two rigid moulds, and a seal is created around the preform. A matrix material, frequently thermoset resin, is injected through one or more inlets placed at various locations in the mould and fills the part. Resin injection pressures of 700 kPa are common. Sometimes, outlet ports connected to vacuum are used to remove volatiles generated as the resin is curing. Drawing a vacuum in the mould can reduce void content and allow a lower injection pressure to be used but voids will form in the matrix if the pressure falls below the vapour pressure of the resin. When the part has been fully infused, cure is initiated by heating the mould. A diagram of the RTM process is shown in Figure 3 [6,8].

Figure 3: Resin Transfer Moulding (RTM)

Advantages

RTM can be used to create near autoclave quality parts with fibre volume fractions as high as 60-70% [9] and void content less than 4% [10]. Because a two-sided rigid mould is used, parts made using RTM have a good surface finish on both sides of the part, with high dimensional tolerances and reproducibility. Furthermore, because the resin is injected under pressure, cycle times of 5-10 minutes can be achieved [10], making RTM well-suited for composite parts made on an industrial scale such as those for the automotive industry [6,8].

Disadvantages

The tooling costs associated with RTM can make it prohibitively expensive. Two-sided matched moulds are required that have been machined to high tolerances, and the tooling must be able to withstand the high resin injection pressures. Furthermore, equipment is required to pressurize the resin and heat the mould [6,8].

2.1.2 Vacuum Assisted Resin Transfer Moulding (VARTM)

Vacuum Assisted Resin Transfer Moulding (VARTM) is a single-sided moulding process that uses vacuum pressure to pull resin through a fibrous preform. In the VARTM process, the preform is layered on a single sided mould, and sealed underneath a flexible vacuum bag. Frequently, a layer of porous distribution medium is placed between the fibres and the vacuum bag. Distribution medium has a low resistance to fluid flow and permits the resin to fill the mould faster.

When vacuum pressure is drawn in the cavity between the bag and the mould, the flexibility of the vacuum bag allows the atmospheric pressure to compress the fibres. Resin inlet ports are located throughout the mould, and the preform is infused by allowing resin to be pulled through the preform by the vacuum pressure. A diagram

of the VARTM process is shown in Figure 4 [6,8].

Figure 4: Vacuum-Assisted Resin Transfer Moulding (VARTM)

Advantages

The tooling costs associated with the VARTM process are significantly lower than with RTM. This is because only a single-sided mould is required, and that mould can be machined from softer material with lower tolerances as it does not have to withstand a high injection pressure or interface with a matching mould. Furthermore, because the preform is under vacuum pressure, the presence of voids will be reduced when compared to hand layup procedures or RTM infusions that do not make use of vacuum pressure [6,8].

Disadvantages

The maximum achievable fibre volume fraction is limited to 50-60% in the VARTM process because only 1 atm of compaction pressure is available to compress the preform [9]. The low pressure available in VARTM infusions also leads to longer fill times when compared to RTM. Simulation tools are frequently used to optimize inlet and outlet placement to ensure the entire preform becomes infused before resin cure.

Furthermore, because a single-sided mould is used, the bagged side of the part will have a lower quality surface finish and low tolerances when compared to the mould side [6,8].

2.1.3 Mouldless VARTM

Maley [3] developed a novel mouldless VARTM technique which can be used to manufacture foam core composite structures. In Maley's method, the single-sided mould is replaced with a rigid foam core which has been machined to the final shape of the part. This foam acts as both the core material in the finished part, as well as the "mould" during manufacturing. The core material is surrounded by the fibre preform, and sealed within a vacuum bag. Resin ports and vents are placed directly on the surface of the part at various locations. Vacuum pressure is drawn inside the bag and the part is infused and allowed to cure. After cure, the rigid foam core remains in the part and provides thickness and strength. A diagram of the Mouldless VARTM process is shown in Figure 5.

Figure 5: Mouldless Vacuum-Assisted Resin Transfer Moulding (VARTM)

Advantages

This technique has several distinct advantages for low cost composite manufacturing: large complex parts can be made to near net shape in a single step, and the foam core significantly increases the strength and stiffness of the final part without adding much weight. Furthermore, the foam core is more machinable than most mould making material, so low production run components can be made for less machining cost and time [3].

Disadvantages

Because the vacuum bag completely encloses the preform, Mouldless VARTM process cannot produce a high quality surface finish like what is attainable using a female mould. The distribution medium tends to leave imprints on the surface of the parts, and the bag will not give a smooth surface finish when compared to female moulds. The resin inlets and outlets must be placed directly on the surface of the part, which causes further degradation of surface finish in the vicinity of these ports. Furthermore, the flexibility of the foam core introduces an additional problem; part warping. Maley and Mahendran discovered that under vacuum pressure, the foam core did not have the stiffness to maintain the desired shape, and the parts tended to cure in a deformed shape unless the core is supported [3, 4].

The mouldless VARTM process is particularly well suited to low production run components, but for larger production runs, significant machining time will be required to machine a foam core for each component [3].

2.1.4 Closed Cavity Bag Moulding (CCBM)

Mahendran [4] developed Closed Cavity Bag Moulding (CCBM), a composite forming process based on the work of Maley. Like Mouldless VARTM, the CCBM process

makes use of a rigid foam core to give the composite parts shape. In the CCBM technique, the preform is completely enclosed in a custom vacuum bag which is manufactured by coating the mould in several layers of silicone with an embedded reinforcement mesh. After the silicone cures, a seam is cut to allow the part to be removed. Flashbreaker tape is bonded to the silicone around the seam to provide a surface to attach a seal. Distribution medium is not used in the CCBM process, but rather a network of distribution channels are moulded directly in to the bag and serve to rapidly transport resin throughout the part and reduce infusion time. A diagram of the CCBM process is shown in Figure 6.

Figure 6: Closed-Cavity Bag Moulding (CCBM)

Advantages

The problem of core deformation in the Mouldless VARTM technique is addressed in the CCBM process by using a custom silicone bag which fits the form of the component more accurately than the single-use bag used in the Mouldless VARTM process. Thus, parts experience less deformation due to residual stresses in the bagging material.

The surface defects caused by the presence of distribution medium and resin ports

are mitigated by manufacturing a system of flow lines directly into the bag. Resin is transported from the inlets to the preform using AirTech Omega Flow Lines [11], and through the preform using resin distribution channels, neither of which leave a significant imprint on the preform. The Omega Flow Lines are shown in Figure 7 separate from (a), and embedded in (b) a silicone bag. Manufacturing of the resin distribution channels is shown in Figure 8.

Figure 7: Omega flow lines shown separate from (a) and embedded in (b) a custom silicone bag

Figure 8: Manufacturing of resin distribution channels in the CCBM process [4]

The CCBM process has an additional advantage; the silicone bag is re-usable, and after the initial time is invested to manufacture the bag, each subsequent infusion is much less labour-intensive. Mahendran [4] performed a Process Value Analysis on the CCBM method and found that manufacturing the silicone bag is cost-effective if more than 3-4 parts are to be manufactured.

The CCBM method is well-suited to manufacturing very complex sandwich structures in a single step. Two GeoSurv II fuselages, shown in Figure 9, were made using this method, and good dimensional tolerances, surface finish, and compaction were achieved.

Figure 9: Fuselage of the GeoSurv II after de-bagging

Disadvantages

Similar to the Mouldless VARTM process, CCBM parts are susceptible to deformation under vacuum pressure and local surface finish damage near inlets and outlets, although these defects have been mitigated through the use of the custom bag, resin flow lines and Omega flow lines. Furthermore, manufacturing the silicone bag is a labour-intensive process, and will add to the manufacturing time. For example, manufacturing the silicone bag for the GeoSurv II fuselage required 15 hours to complete [4].

2.2 Factors affecting composite part quality

When optimizing the VARTM procedure, four parameters were used to quantify the quality of composite components; fibre volume fraction, void content, dimensional

tolerance, and surface finish. These four parameters, as well as common defects that have been encountered during the manufacturing of GeoSurv II components, are discussed below.

2.2.1 Fibre volume fraction

The ratio of fibre volume to the total volume of a composite structure is called the fibre volume fraction. The tensile, compressive, and shear strength of composite structures are proportional to fibre volume fraction [12, 13], so it is important to achieve parts with as high a fibre volume fraction as possible to maximize strength.

The maximum fibre volume fraction achievable when using atmospheric pressure to compact the preform is limited to 50-60%. However, the actual fibre volume fraction achieved in VARTM components can be lower than this theoretical limit due to thickness gradients within the preform. These thickness gradients develop during infusion because while the fluid is at nearly vacuum pressure near the flow front, it is at approximately atmospheric pressure near the inlet. As a result, the preform near the inlet will be significantly thicker than in the vicinity of the outlet while still containing the same volume of reinforcement. Often, the inlets are connected to a vacuum port to remove excess resin after the part has been infused. However, if the resin gels before it can be fully removed from the preform, significant thickness variations can remain in the part. This excess resin decreases the strength of the part and increases its weight.

2.2.2 Void content

A void is defined as any area of a composite structure where neither matrix nor reinforcement material are present, and is frequently caused by air bubbles or volatiles trapped in the resin during cure [14]. The presence of voids has a significant impact on

the properties of composite lamina, particularly resin-dominated properties such as shear modulus. For example, when the void content in composites is increased from 1% to 5%, a reduction in tensile strength between 15-50%, and modulus between 7-33% can be expected [15].

There are several methods that have been used to measure the void content of composite lamina such as resin burnout, acid digestion, thermogravimetric analysis, and point count metallography. [15] contains a description of these methods.

The formation of voids is generally caused by two phenomena: off-gassing of volatiles, and entrapped air. Off-gassing occurs when a sufficiently low vacuum pressure is generated in the mould, and the vapour pressure of dissolved solvents within the resin exceeds the local hydrostatic pressure. Air can become trapped in the resin during processing if bubbles are allowed to form during resin mixing, if the mould cavity is not sealed properly, or if the resin cures before the preform has become fully saturated causing a "dry spot" [14].

Two modes of void accumulation have been observed by Carleton researchers: large void accumulation in part corners, and dry spot formation due to incomplete infusion. Both these phenomena were observed in the infusion of the GeoSurv II fuselage. The corner void accumulation observed in the fuselage is shown in Figure 10. The dry spots left in the fuselage after infusion are shown in Figure 11.

Figure 10: Void accumulation in the inside corner of the GeoSurv II fuselage after infusion

Figure 11: Dry spots in the GeoSurv II fuselage from incomplete resin infusion

2.2.3 Dimensional tolerances

Achieving high dimensional tolerances is always a challenge when manufacturing composite parts. In particular, when single-sided moulding processes are used, the dimensional tolerance of part thickness is an issue. Even autoclave parts can only be manufactured to within 5% nominal thickness using a single-sided mould [6]. This issue can be mitigated in VARTM processes through the resin emptying procedure described above, but cannot be completely eliminated.

Another cause of poor dimensional tolerances in composite parts is warping due to residual stresses created when curing occurs at an elevated temperature. Differences in thermal expansion coefficient between the mould and the preform will lead to residual stresses and warping upon de-moulding [7]. Part warping can also be caused by cure gradients, shrinkage, and non-uniformity in the resin [16]. However, all processes studied at Carleton have a room-temperature cure cycle, so these issues are largely avoided.

Mouldless VARTM and CCBM processes have an additional cause of dimensional variability: part warping due to core deformation under vacuum pressure. In these processes, the foam core is responsible for maintaining the shape of the composite during infusion, and because the foam core lacks the stiffness of a rigid mould, deformations have been observed in the cured parts. The deformation was characterized by Mahendran who measured the distance between the left and right walls of the GeoSurv II fuselage, and found up to 3.0% deviation from the as-designed width, which was caused by part warping [4]. However, when a rigid jig was used to support the fuselage walls, the maximum deviation from the designed value was reduced to 1.8%.

2.2.4 Surface finish

Achieving a smooth, flat surface finish on composite parts can be important for some applications. Surface finish is a particularly important parameter for aerodynamic surfaces or for parts that will be painted. The process used to form a composite part determines the quality of surface finish that will be produced. For example, both faces of parts made using the RTM process will have a high-quality surface finish, whereas only one side of parts made using VARTM will have a smooth finish. The surface finish of parts made using either Mouldless VARTM or CCBM will not have a smooth surface finish on any side.

In general, two types of surface finish have been observed in parts produced at Carleton; that made using a female mould, and that made using the interface between the preform and a vacuum bag. Female mould surface finishes are extremely smooth and flat, and if care is taken when polishing the mould they can have a high gloss. An example of a female mould surface finish is shown in Figure 12.

The finish produced on surfaces contacting the vacuum bag will be rough and contain thickness variations. Peel Ply, a nylon film, is used to prevent the vacuum bag and distribution medium from bonding to the surface of the preform, and leaves a pattern imprinted on the surface of the laminate. Folds in the vacuum bag can also result in linear defects on the surface. The type of surface produced by the Peel Ply layer is shown in Figure 13.

Figure 12: Surface finish produced using a female mould

Ridge caused
by wrinkle in
vacuum bag

Figure 13: Surface finish produced using a Peel Ply layer

The use of distribution medium can cause leave deep imprints in the surface of the

laminate, and should be avoided in parts that require a smooth surface. An example of the type of imprints left by distribution medium is shown in Figure 14.

Figure 14: Surface finish defects caused by the use of distribution medium

2.3 Discussion of LCM processes

LCM processes are well suited to manufacture high-quality components without large costs associated with autoclave processes. VARTM, Mouldless VARTM, and CCBM have been used successfully to manufacture components for the GeoSurv II UAV, and were considered for the GeoSurv II mission avionics hatch and inverted V-empennage.

Manufacturing trials conducted by LCC researchers have shown that degradation of surface finish, deformation of parts, formation of voids, and poor compaction are common manufacturing defects found in LCM parts. Chapters 3 and 4 describe the development and use of simulation tools to prevent dry spot formation and improve fibre volume fraction in VARTM components. Chapter 5 describes an experimental method used to characterize and reduce thickness variations and void formation in part corners.

Chapter 3

Selection of flow simulation software

Process simulation software is widely used to predict and model the progression of resin through a fibrous preform in many LCM processes, including VARTM [17]. These simulation tools have been extensively used to predict flow front progression, resin pressure, resin cure, resin flow rate, and resin temperature in many infusion processes [8].

For this research, a simulation tool was required to simulate the VARTM infusion process to avoid dry spot formation, and predict resin emptying behaviour. When choosing a software, the following features were required:

1. **Simulation of VARTM infusions:** Many simulation tools assume a constant permeability throughout the preform, which is true for RTM infusions, but does not accurately model the VARTM infusion process. It was necessary to choose simulation software that incorporates a model of preform compaction during mould filling to accurately describe the VARTM process.
2. **Simulation of three-dimensional parts:** The chosen software must be able to simulate the infusion of three-dimensional parts.
3. **Low cost:** Reducing the cost of manufacturing VARTM components is a focus of this research. The selected simulation tool should be as inexpensive

as possible, with minimum contribution to the overall cost of the composite manufacturing.

4. **User-modifiable code:** This software will be used as a research tool, so it was desirable to be able to modify the code that is run during simulation. This will allow a greater level of control over the simulation, and provide an opportunity to test new simulation techniques.
5. **Resin cure model:** The accuracy of an infusion simulation is improved by incorporating a resin cure model. Furthermore, resin cure is an important parameter when simulating resin emptying. For these reasons the simulation tool is required to have the ability to incorporate a resin cure model.
6. **Low development time:** The focus of this research was not the development of a simulation tool, but rather its use to optimize composite manufacturing. For that reason, a significant amount of time should not be required to develop or modify the chosen simulation tool.
7. **Simulation of resin emptying:** The chosen software should either have a built-in capability to simulate resin emptying, or be modifiable to include a resin emptying simulation.

The following section describes four different software tools that were investigated using the requirements developed above.

3.1 Overview of available software

Four different software solutions were investigated as possible simulation tools for this research. Each software was evaluated against the criteria developed above, and

two simulation programs were chosen to simulate mould filling and resin emptying in VARTM infusions.

3.1.1 Liquid Injection Moulding Software (LIMS)

LIMS is a tool for simulating the mould filling stage of RTM infusions that was developed by the University of Delaware Center for Composite Materials. LIMS uses a finite element method to model resin flow front motion during the infusion and can be run from a GUI, as well as from the command line. The user is able to control and modify the simulation process using the LBASIC coding environment, and can modify all relevant material properties, such as permeability and resin viscosity, throughout the infusion. A screenshot of the LIMS GUI is shown in Figure 15 [18]. The advantages and disadvantages of this software are listed below.

Figure 15: Screenshot of the University of Delaware's LIMS software [18]

Advantages

- LIMS can be used to model two and three-dimensional components [18].
- The user can modify the simulation using LBASIC scripts [18].
- LIMS is relatively inexpensive, and a trial version is available for development [18].
- LIMS can accept user-defined resin cure models [18].

Disadvantages

- LIMS is not able to simulate resin emptying [18].
- LIMS is currently designed to simulate RTM infusions. However, because the user can modify the simulation using LBASIC scripts, LIMS can be modified for VARTM infusions but this requires significant development time [18].

3.1.2 PAM RTM

PAM RTM is a software package made by the ESI Group that can be used to simulate many LCM processes including RTM, VARTM, and VARI. PAM RTM can simulate the infusion process, but also includes several other features such as a fabric draping model, estimate of optimal injection location, automatic flow rate control and sequential opening and closing of gates [19]. A screenshot of PAM RTM is shown in Figure 16. The advantages and disadvantages of this software are listed below.

Figure 16: Screenshot of ESI Group's PAM RTM [20]

Advantages

- PAM RTM is a commercial product that comes ready to simulate VARTM infusions with no development time. It comes built in with all of the functionality to simulate a VARTM infusion of three-dimensional components and has the capability to simulate resin cure [19].
- PAM RTM includes several specialized routines such as a mould draping simulation and an optimal injection port location calculator that could prove to be useful for this research [19].

Disadvantages

- PAM RTM costs between \$5,000 and \$8,000 for a yearly educational license, which is above the budget allotted to the simulation software [21].

- The software has no native ability to simulate mould emptying.
- There is no access to the code and no ability to change or modify how the simulation is being run. For commercial purposes this is good, but as a research tool it is desirable to have more control over the simulation process.

3.1.3 RTM-Worx

RTM-Worx is a simulation tool developed by PolyWorx that uses a Finite Element Method to simulate RTM infusions. RTM-Worx was designed to be a simple-to-use simulation tool for RTM process optimization, and has a built-in meshing capability [22]. A screenshot of RTM-Worx is shown in Figure 17. The advantages and disadvantages of this software are listed below.

Figure 17: Screenshot of Polyworx's RTM-Worx [22]

Advantages

- RTM-Worx is able to simulate the infusion of three-dimensional parts [22].

Disadvantages

- RTM-Worx costs approximately €13,000 for a yearly license, which is significantly above the budget allotted to the simulation software [23].
- RTM-Worx can not accept a resin cure model [22].
- The user does not have access to the PolyWorx code [22].
- RTM-Worx is not able to simulate VARTM infusions [22].
- RTM-Worx does not have a mould emptying simulation built in to the software [22].

3.1.4 Development of in-house model

The final option that was considered for flow simulation software was the development of an original model capable of performing simulations of the infusion process for various preform geometries. The advantages and disadvantages of this approach are listed below.

Advantages

- Because the model is being developed specifically for this application, features such as a resin cure model and compaction model for VARTM infusions can be programmed into the simulation.
- The code can be purpose-built to simulate the resin emptying process.

- Because all of the code is written in-house, the user will have complete control over the mathematical processes behind the simulation.

Disadvantages

- Because this model would be built from scratch, significant development time would be required, even for a one-dimensional model.
- The time required to develop three-dimensional modelling capabilities is beyond the scope of this research.

3.2 Selection of flow simulation software

A weighted trade-off study was implemented to evaluate the four software tools against the criteria developed above. Each software package was evaluated on a scale of one to three for each of the seven requirements. The results of the trade-off study are shown in Table 2.

Category	LIMS	PAM-RTM	RTM-Worx	In-house simulator
VARTM capability	3	3	0	3
3D shell capability	3	3	3	1
Low cost	3	2	1	3
User-modifiable code	3	0	0	3
Resin cure model	3	3	0	3
Development time	2	3	3	1
Simulation of mould emptying	0	0	0	3
Total	17	14	7	17

Table 2: Weighted trade study of flow simulation software

Based on this trade-off study, two software solutions emerge as clear favourites; LIMS, and the development of an in-house model. However, each of these two options has its own shortcoming. Although LIMS can be used to simulate three-dimensional components, it does not have a built-in method for simulating mould emptying. An in-house model on the other hand can be written to simulate mould emptying, but it would be too time-intensive to develop three-dimensional simulation capabilities for this model. For that reason, a combination of both software solutions was implemented. LIMS was used to simulate the mould filling process with modified LBASIC code to incorporate the effects of compaction for VARTM infusions. Then, an in-house numerical model was developed to simulate resin emptying in one dimension.

These two simulation tools provide an inexpensive method to simulate both mould filling and resin emptying for VARTM infusions. The filling of three-dimensional

components was simulated to predict fill time and dry spot location. Then, a one-dimensional resin emptying simulation was used to predict thickness variation at cure.

Chapter 4

VARTM resin flow simulation

Both the modification of the LIMS software to incorporate VARTM effects and the development of a resin emptying simulation require a governing equation to model resin motion. When simulating the movement of resin through a porous preform due to the pressure gradient caused by the application of vacuum pressure, a relationship between applied pressure and fluid motion must be used. It is desirable to avoid using the full momentum equations of fluid flow because the complexity of thousands or millions of resin channels through the individual fibres leads to impractically complicated and time-consuming simulations [8].

Most flow simulation software for LCM processes use Darcy's Law [24], a semi-empirical relationship developed to quantify the underground flow of water through sand, in combination with continuity equations to numerically solve for the flow front position as a function of time [8, 25–31]. The following sections discuss the practical application of Darcy's Law to LCM flow simulations, and present a method to incorporate a flexible bag and resin cure into the simulation. An algorithm to control the LIMS simulation to incorporate VARTM effects is presented, and a resin emptying model is developed and implemented in MATLAB.

4.1 Darcy's law

A semi-empirical relation called Darcy's law was developed to characterize the motion of liquid through a porous medium [24], and has been used to simulate the infusion of a fibrous reinforcement by resin in LCM processes. A formulation of Darcy's law [8] that can be used to simulate a one-dimensional flow front in an LCM process is given by Equation 1.

$$Q = \frac{K A}{\mu} \frac{dP}{dx} \quad (1)$$

where Q is the volume flow rate through cross section A , μ is the resin viscosity, $\frac{dP}{dx}$ is the spatial gradient of pressure at a given point in the fluid flow, and K is the permeability of the fabric. Permeability is a measure of the resistance of the fabric to fluid motion determined experimentally or calculated using fibre volume fraction, orientation, and geometry.

Equation 1 is frequently rearranged so that the fluid motion can be expressed using the Darcy velocity [8]. This is shown in Equation 2.

$$u = \frac{K}{\mu} \frac{dP}{dx} \quad (2)$$

where the Darcy velocity u is equal to the volume-averaged fluid velocity [32] and is given by Equation 3 below:

$$u = \frac{Q}{A} = v(1 - \nu_f) \quad (3)$$

where u is the Darcy velocity, v is the interstitial resin velocity, and ν_f is the fibre volume ratio of the preform.

4.1.1 Darcy's law for general three-dimensional resin flows

The general form of Darcy's law for a three dimensional anisotropic porous medium is given in Equation 4.

$$\bar{\mathbf{v}} = \frac{\mathbf{K}}{\mu(1 - \nu_f)} \nabla P \quad (4)$$

which can be expressed in matrix notation as shown in Equation 5.

$$\begin{pmatrix} \bar{v}_x \\ \bar{v}_y \\ \bar{v}_z \end{pmatrix} = -\frac{1}{\mu(1 - \nu_f)} \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix} \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \\ \partial P / \partial z \end{pmatrix} \quad (5)$$

If it is assumed that the thickness of the preform is small when compared with its area, then the motion of the resin in the z direction can be neglected. Furthermore, if it is assumed that the principal directions of the permeability tensor coincide with the x and y axes of the coordinate system, then Equation 5 can be reduced to the following equation [8]:

$$\begin{pmatrix} \bar{v}_x \\ \bar{v}_y \end{pmatrix} = -\frac{1}{\mu(1 - \nu_f)} \begin{pmatrix} K_{11} & 0 \\ 0 & K_{22} \end{pmatrix} \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \end{pmatrix} \quad (6)$$

When solving Equation 6 for a two-dimensional LCM infusion, the following boundary conditions are used:

- Inlet pressure is approximately equal to atmospheric pressure ($P_{inlet} \approx P_{atm}$) [32]
- Resin pressure at the flow front is equal to the vacuum pressure achieved in the cavity ($P_{flowfront} = P_{vacuum} \approx 0$) [32]

Using Equation 6, the permeability tensor can be determined from the permeability in the two principal directions. The permeability of the fabric in any other direction can then be determined using coordinate transformations.

Flow simulation software such as LIMS is used to solve Equation 4 when flow through the thickness of the preform is significant, or Equation 6 when flow through the thickness of the preform can be neglected [25, 33].

4.1.2 Infusion simulation of complex three-dimensional shapes

To reduce computational load when simulating an infusion, flow through the thickness of the preform is often neglected, and the preform is modelled as a two-dimensional shell. However, preform deformations due to three-dimensional corner geometry have been proposed as one area where flow front motion could deviate from what is predicted using a strictly two-dimensional model. The following two mechanisms could cause the fluid pressure loss around a corner to deviate from the value predicted from flat-plate theory:

1. As fluid flows around a corner, it experiences a centripetal acceleration that causes swirling secondary flows in the fluid. These secondary flows could cause additional pressure losses that are not predicted by flat plate-theory [34].
2. The fluid pressure on the inner wall of the corner is lower than that of the outer wall due to the centripetal acceleration [34]. This pressure gradient could lead to a component of fluid flow in the radial direction, which is not modelled in flat-plate theory.

Advani *et al.* studied the effects of corner radius on flow front motion using rigid two-sided moulds with radii between 1.5 mm and 200 mm and found that moulds

containing corners of smaller radii required higher injection pressure to achieve the same resin flow rate during an infusion [35]. The thickness of the mould cavity in the vicinity of these corners was found to deviate from the nominal flat-plate thickness, so simulations were performed to compensate for the change in preform permeability due to the observed thickness variations. These simulations showed that the dependency of injection pressure on corner radius could be completely explained by the permeability changes due to thickness variation of the preform in each corner of the mould [36]. Therefore, the two mechanisms described above did not significantly effect the fluid flow.

The studies performed by Advani *et al.* show that the only special consideration that needs to be made when modelling the effects of complex corner geometry is for the permeability variation due to nonuniform fibre bed compaction in the vicinity of part corners [35]. Rather than attempting to predict the magnitude of any thickness variations that would occur under a flexible bag and their effect on flow front motion, a method for minimizing the variations was developed, and is discussed in Chapter 5. The relationship between preform permeability and compaction in VARTM infusions is discussed in the following section.

4.2 Effects of bag flexibility in the VARTM process

When simulating VARTM infusions, the dependency of preform permeability on fibre compaction must be considered. To model the effects of the varying preform thickness, a relationship between fibre volume fraction and compaction pressure is developed below. The permeability of the preform is then related to fibre volume fraction using an experimental method.

4.2.1 Relationship between fibre volume fraction and compaction pressure

Unlike RTM processes, the flexible bag used to provide compaction pressure in VARTM manufacturing allows the thickness of the preform to vary during infusion as a function of resin pressure [32,37]. When a vacuum is drawn in the mould cavity, the pressure differential across the vacuum bag is supported by both the resin and the preform. The compaction pressure on the preform can be calculated using Equation 7 as shown below:

$$P_{atm} = P_{comp} + P_{resin} \quad (7)$$

where P_{atm} is the atmospheric pressure outside of the mould cavity, P_{comp} is the compaction pressure applied to the fibrous preform, and P_{resin} is the pressure of the resin.

A pressure gradient exists in the resin as it flows through the preform, and therefore P_{resin} also varies between the inlet and the flow front. As a result, the pressure supported by the preform is constantly changing throughout the infusion, causing variations in the thickness of the preform. This phenomenon is shown in Figure 18.

Figure 18: Changes in compaction pressure experienced by preform due to fluid pressure [38]

Researchers [31, 39, 40] have empirically related the fibre volume fraction of the preform to compaction pressure using Equation 8 as shown below:

$$v_f = v_{f0} P_{comp}^B \quad (8)$$

where v_f is the fibre volume fraction, v_{f0} is the fibre volume fraction with a compaction pressure of 1 Pa, and exponent B is experimentally determined. The units of pressure used when deriving B must be consistent when using Equation 8.

Equation 8 was used to characterize the compaction behavior of two layups of carbon fibre cloth. The results of the compaction experiments are shown in Section 4.4.

4.2.2 Permeability as a function of volume fraction

During preform compaction, the spacing between individual fibres decreases and flow channels are constricted. As the fluid is forced to flow through smaller and smaller spaces, the pressure losses in the fluid increase leading to a decrease in permeability [8].

Several relationships have been proposed to relate fibre volume fraction to preform permeability. The Kozeny-Carman Equation, shown in Equation 9 below, is a commonly used relation that was developed using a capillary model from soil mechanics [8, 9, 41].

$$K = \frac{1}{s^2 k} \frac{(1 - v_f)^3}{v_f^2} \quad (9)$$

where v_f is the fibre volume fraction, s is the specific surface of the fibres and k is the Kozeny constant. Theoretically, k has a value of 2 for a bed of aligned cylindrical fibres but Skartsis [42] has shown that the measured value of the Kozeny constant will deviate significantly from its theoretical value due to the non-uniform nature of the fibres. However, Astrom *et al.* [43] have shown that k is approximately constant for

fibre volume fractions between 0.3 and 0.7. This allows Equation 9 to be expressed as shown below:

$$K = k_0 \frac{(1 - v_f)^3}{v_f^2} \quad (10)$$

where k_0 is an empirically derived constant that is dependent on fibre geometry, orientation, curvature (tortuosity), and volume fraction.

Several researchers [32, 44, 45] have used an exponential relation, shown below, as an alternative to the Kozeny Carman equation.

$$K = A_1 v_f^{b_1} \quad (11)$$

where A_1 and b_1 are experimentally determined constants. This method, however, has the disadvantage that two empirical constants need to be determined, whereas only one is required to use Equation 10. This can increase the complexity involved with experimentally determining the permeability relationship.

Experimental methods for relating permeability to preform compaction

Several researchers [8, 45] have used a permeability apparatus where the fibre preform is held in a rigid, two-sided mould. Resin is injected at a constant pressure, and flow front location is recorded as a function of time. Stadtfeld [46] describes a method of characterizing permeability where resin is injected into a rigid, two-sided mould at a constant flow rate. Using this method the permeability of the specimen can be related to the change in injection pressure. For both methods, v_f is held constant for each experiment, and experiments are performed over a range of v_f values. Both of these methods require considerable work to design and manufacture the permeability measurement fixture, as well as considerable time to perform the experiments for a range of fibre volume fractions.

In an attempt to simplify the measurement of permeability, several researchers [3, 44, 47] have assumed that permeability is constant, and calculated an equivalent "VARTM permeability". This method can produce accurate results, but simulation results will deviate for specimens that are much different in size than the specimens that were used to calculate the K values.

A method of characterizing permeability was developed in this project that involves a series of VARTM panel infusions, similar to what was done by Maley [3]. The flow front motion of each infusion was then used to characterize the permeability of the fibre as a function of fibre volume fraction. This technique does not require complex moulds and many trials like the two-sided mould methods, but unlike the work done by Maley, can be used to determine the relationship between fibre volume fraction and permeability.

The permeability characterization technique was based on studies performed by Gokce [33], who used an algorithm to estimate permeability through comparison to simulation. Gokce's method was modified in this study to include effects due to the compaction of the preform, and did not include a layer of distribution medium. In the new method, flow front measurements from flat-panel VARTM infusion experiments are compared against a VARTM LIMS simulation of the same panel infusion. It is assumed that the relationship between permeability and fibre volume fraction obeys the modified Kozeny-Carman equation shown in Equation 10 which allows the flow front location to be characterized using only a single experimental parameter. The permeability characterization algorithm, shown in Figure 19, iteratively adjusts the value of k_0 to minimize the sum of the squares of the difference between the experimental flow front position and the simulated flow front position over the length of the infusion. The k_0 value which leads to the minimal sum-of-squares value can be considered an optimal estimate of actual fibre permeability, which encompasses the effects of fibre orientation, size, geometry and compaction.

Figure 19: Algorithm used to fit k_0 used in LIMS simulation to experimental flow front data

To use the method shown in Figure 19 to characterize the permeability as a function of compaction, the user scripts must be written for the LIMS software to incorporate the flexible bag found in a VARTM infusion through the Kozeny-Carman equation. This process is described in Section 4.3.

4.2.3 Viscosity cure model

A predominant empirical viscosity model for the cure of a two-part epoxy resin [48] is shown in Equation 12. This model describes the resin viscosity $\mu(t, T)$ at time t and absolute temperature T .

$$\ln \mu(t, T) = \ln(\mu_\infty) + \frac{\Delta E_\mu}{RT} + tk_\infty \exp\left(\frac{-\Delta E_k}{RT}\right) \quad (12)$$

where μ_∞ , ΔE_μ , R , k_∞ , and ΔE_k are properties of the resin and can be considered constant over the cure cycle. If isothermal conditions are assumed, Equation 12 can be re-written as:

$$\ln\left(\frac{\mu(t)}{\mu_\infty}\right) = \alpha + \beta t \quad (13)$$

where α and β are constant over the cure and are functions of temperature and resin properties. Equation 13 can be used to relate the resin viscosities at t_1 and t_2 of a cure cycle as shown below:

$$\frac{\mu_1}{\mu_2} = \frac{e^{\alpha+\beta t_1}}{e^{\alpha+\beta t_2}} \quad (14)$$

If it is assumed that μ_2 is the initial viscosity at $t = 0$, then Equation 14 can be reduced to the following:

$$\frac{\mu}{\mu_0} = e^{\beta t} \quad (15)$$

which can be used to relate resin viscosity at time t to its initial viscosity μ_0 and a parameter β which is a function of temperature and resin material properties. This parameter will be experimentally derived in Section 4.4.3.

4.3 Simulation of VARTM infusions using LIMS

The software package that was chosen to perform the VARTM mould filling simulations was LIMS. LIMS was developed at the University of Delaware Center for Composite Materials and uses a Finite Element/Control Volume method to predict and model resin flow in RTM mould filling processes [49]. LIMS can be run either from a command line program, or through a graphical user interface and requires the following input parameters to perform a simulation of an RTM filling process:

- Mould geometry. LIMS accepts meshed geometries in the ABAQUS input file format.
- Preform permeability, thickness and fibre volume fraction.
- Resin viscosity, cure data.
- Inlet and outlet placement.
- Location and size of flow channels, if applicable.

LIMS is able to use these parameters to predict flow front progression, pressure distribution, and flow rates during constant permeability infusions. Methods for the setup and operation of LIMS have been described in detail in literature [3, 50].

In order to incorporate the flexible bag nature of the VARTM infusion process into a LIMS simulation, the values for permeability, fibre volume fraction, and thickness must continually be updated based on local resin pressure throughout the simulation. A method for iteratively modifying these values at each simulation time step has been developed for VARTM simulations and is based on an algorithm used by Correia *et al.* [38]. Conceptually, this algorithm is shown in Figure 20.

4.3.1 Incorporation of cure data into the LIMS model

The effects of resin viscosity increase during cure were incorporated into the LIMS simulation by modifying the permeability at each time step in proportion to the ratio of the viscosity increase calculated using Equation 15. The modified form of Equation 10 which treats the effects of resin cure as a change in permeability is shown below and was implemented in the LIMS simulation.

$$K' = \frac{k_0}{e^{Bt}} \frac{(1 - v_f)^3}{v_f^2} \quad (16)$$

Figure 20: Algorithm used in LBSIC script for LIMS VARTM simulation

4.4 Characterization of permeability, compaction, and resin cure

The preform and resin must be characterized before VARTM infusions can be simulated using the method described in the previous section. The experimental methods that were used to characterize the compaction, and permeability of the preform, and cure behavior of the resin are described in the following sections.

4.4.1 Measurement of compaction behavior

A two-plate apparatus was used to measure the deformation of the preform under load. A compressive force was applied to a fibre bed through parallel platens, and force-displacement graphs were generated of the resulting deformation. These plots were used to determine the relationship between pressure and fibre volume fraction.

Two different layups of BGF 94107, the 8 harness satin woven cloth to be used on the GeoSurv II empennage and fuselage hatches, were characterized. The ply orientations that were tested are shown in Table 3.

Table 3: 2 Ply and 3 ply layups used in compaction testing

Layup	Fibre orientation
2 Ply	[(0°, 90°), (45°, -45°)]
3 Ply	[(0°, 90°), (45°, -45°), (90°, 0°)]

Experimental apparatus

An apparatus was constructed with two parallel ground steel plates (159 mm × 82 mm). The top plate was free to move in a direction normal to its face, but constrained in all other directions. It was important to ensure that the steel plates remained parallel throughout the experiment, so they were mounted on cylindrical guides. Measurements of the separation between the plates were taken at several different locations to ensure that the plates were completely parallel. No deviations were measured on the digital calipers. The two-platen apparatus used for the compaction experiments is shown in Figure 21.

Figure 21: Apparatus for measuring fibre compaction behaviour

To account for the lubrication effects due to the resin [51,52], "wet" compaction measurements were taken by first saturating the carbon layups with an aqueous glycerol solution. Work done by Maley [3] on the characterization of the viscosity of aqueous glycerol for different temperatures and water concentrations was used to select an appropriate water concentration.

Robitaille [39,51] used a two-platen apparatus to characterize fibre compaction behaviour. The apparatus contained pressure sensors to measure the pressure supported by the resin due to its horizontal motion. The resin pressure was then subtracted from the applied pressure to determine the pressure supported by the fibre alone. For simplicity, the apparatus used for the compaction experiments in this research did not make use of pressure transducers. A low loading rate was used to ensure that fluid motion did not significantly affect the results. Initially, a compaction rate of 0.61 mm/min was used, but it was found that after the maximum load was reached, the load would decrease with the displacement held constant. This was attributed to

effects of fluid motion within the fibre bed, so the loading rate was reduced to 0.16 mm/min to mitigate these effects.

A Material Test System (MTS) 810 load frame with a 25 kN capacity was used under displacement control to conduct the compaction measurements. The load cell had an accuracy of ± 12.5 N. A test was first performed with no fibre bed between the platens so that the deflection of the apparatus alone could be measured and subtracted from the results. The two-platen apparatus mounted in the MTS frame is shown in Figure 22.

Figure 22: Apparatus for measuring fibre compaction behaviour

Results of the compaction experiments

Three trials were done on each of the two fibre layups. Load-displacement plots were generated by the MTS software and were used to plot fibre volume fraction against compaction pressure. A MATLAB exponential curve fit was used to determine v_{f0} and B . The plot of fibre volume fraction against compaction pressure is shown in Figure 23 for the 2 ply layup, and Figure 24 for the 3 ply layup. Each plot contains data from the three experimental trials, as well as the resultant curve fit. Figure 23 shows how the first compaction trial performed on the 2 ply layup deviates slightly from the other two. This trial was performed at a higher loading rate, and was neglected for reasons discussed above.

Figure 23: Compaction measurements for 2 ply carbon layup

Figure 24: Compaction measurements for 3 ply carbon layup

The average values of v_{f0} and B for the 2-ply and 3-ply layups, along with the standard deviation of each set of measurements are shown in Table 4.

Table 4: Experimentally determined compaction data for two and three plies of carbon fibre cloth

Layup	v_{f0}	σ	B	σ
2 Ply	0.080	0.0036	0.162	0.013
3 Ply	0.079	0.0018	0.162	0.0044

4.4.2 Measurement of preform permeability

Test infusions were performed on flat rectangular specimens of two-ply BGF 94107 carbon fibre fabric, and flow front motion was tracked and recorded. The flow front data was then used in the algorithm shown in Figure 19 to determine predictions for k_0 .

The test specimens had a ply orientation of $[(0^\circ, 90^\circ), (45^\circ, -45^\circ)]$ and were $0.381 \text{ m} \times 0.0762 \text{ m}$ in size. The apparatus used to track flow front location consisted of a flat glass tool plate with a rectangular carbon fibre test specimen on its surface. The test specimen was sealed under a vacuum bag, and spiral flow channels were placed at either end of the specimen to ensure a linear flow front. One end of the rectangular specimen was attached to a vacuum pump through a resin catch pot and the other was attached to a resin flow line. A video camera was mounted directly above the specimen to record flow front location and a ruler was mounted parallel to the specimen along its edge. The test setup is shown in Figure 25.

Figure 25: Setup of permeability measurement apparatus

Selection of fluid for permeability experiments

The effects of resin cure on flow front motion were removed by using aqueous glycerol instead of epoxy resin for the permeability measurement infusions. Aqueous glycerol was chosen as an infusion fluid because it has a constant viscosity, is safe to work with and is easy to clean up. Aqueous glycerol with a viscosity of 3.3×10^{-4} Pa s was used in order to match the viscosity of the PTM&W PT2712 epoxy resin system [53] – the resin system that will be used for the GeoSurv II empennage and hatches, as well as the corner test pieces. Aqueous glycerol with equal viscosity was used in the

permeability measurements because the viscosity of the fluid has been shown to affect preform permeability by Gauvin *et al.* [54]. It was therefore important to match the viscosity of the aqueous glycerol to that of the resin.

Maley [3] characterized aqueous glycerol viscosity as a function of water content and temperature, and this data was used to match the aqueous glycerol viscosity to that of the resin. The temperature of the lab was measured to be 23°C, so from Maley's work, a water concentration of 6% by mass was used in the aqueous glycerol to match the viscosity of the PT2712 resin.

Infusion pressure used for permeability experiments

It is desirable to perform VARTM infusions with the maximum achievable vacuum pressure available from the pump, as this causes a faster infusion time and greater preform compaction. For that reason, the permeability experiments were performed at the pump's maximum vacuum pressure. Due to variations in atmospheric pressure and bag seal, the vacuum pressure that was achieved during the permeability experiments ranged from 96.5 kPa to 98 kPa. The vacuum pressure for each trial was recorded and accounted for in the permeability estimation algorithm.

Digitization of the flow front

Maley [3] used a digital image capture algorithm to digitize the flow front automatically. However, it was determined that the positional accuracy of approximately ± 4 mm that could be obtained by mounting a ruler beside the specimen, and manually reading off flow front locations at various times throughout the video was sufficient.

Sample data taken during an infusion trial is shown in Figure 26. The ruler scale is visible in the infusion video, and was used to approximate flow front location.

Figure 26: Measurement of permeability using video technique

Race-tracking during permeability measurements

Race-tracking is a phenomenon whereby the fluid flows preferentially through flow paths caused by folds in the bag and along the edge of the preform, and should be avoided when performing permeability experiments [8, 54]. Folds were manually removed from bag as vacuum pressure was being drawn. During the infusion, negligible race-tracking was observed due to edge effects, as shown in Figure 26, so it was assumed that race-tracking was not a major source of error in the permeability measurements.

Effects of bag deformation on preform permeability

Two types of bagging material were tested in the permeability experiments; a highly flexible Stretchlon bag, and a standard vacuum bag with lower flexibility. Stretchlon bagging material is made from Hytrel, a thermoplastic polyester elastomer [55, 56], and is designed to conform to complex three-dimensional moulds. Stretchlon bag has a maximum elongation of approximately 600% [57] and is thus able to conform tightly to complex mould shapes. It was found that the permeability of the preform under the high flexibility bag was significantly lower than under a more rigid bag. This was attributed to the Stretchlon's ability to nest between the fibres more closely, and thus close off some of the flow channels on the surface of the preform. A similar phenomenon was documented by Zhang *et al.* [58], who studied the effects of the flexible bag nesting into the contours of the distribution medium. This bag nesting closed off flow channels created by the distribution medium, and thus reduced permeability of the preform. For that reason, the fibre permeability was measured for two bagging techniques; using the high flexibility Stretchlon bag, and using the low flexibility bag.

Results of the permeability experiments

The permeability of the two-ply layup was measured using the method described above. A plot of flow front location with time for the low flexibility bag along with the predicted flow front motion using the permeability estimation algorithm is shown in Figure 27.

Figure 27: Permeability measurements for 2 ply carbon layup with low flexibility bag

The average values of k_0 for the 2-ply layup under the low flexibility and high flexibility bags, along with the standard deviation of each set of measurements are shown in Table 5.

Table 5: Permeability of 2 ply carbon layup bagged using two different materials

Layup	k_0 (m ²)	σ
High flexibility bag	0.76×10^{-11}	0.066×10^{-11}
Low flexibility bag	1.45×10^{-11}	0.137×10^{-11}

4.4.3 Measurement of resin viscosity during cure

In Darcy's law, the speed at which the flow front advances is inversely proportional to resin viscosity, and this relationship was used to characterize the change in resin viscosity as it cures.

Infusions of short test specimens of two-ply BGF 94107 were performed with resin in various stages of its cure cycle. The increase in infusion time as the resin cures was related to the increase in resin viscosity. 102 mm test specimens were used to reduce infusion time so that the viscosity of the resin could be assumed to be approximately constant over the length of an individual specimen infusion. Isothermal resin conditions were also assumed throughout the infusion.

The experiment was run by mixing a single pot of PT2712 resin, and infusing a 102 mm specimen every 45 minutes. For each infusion, the flow front was tracked, and the time taken for the flow to travel 51 mm, 76 mm, and 102 mm was measured. The results of this experiment are shown in Figure 28.

Figure 28: Plot of infusion time to reach various lengths at different resin cure states

For each infusion performed at time t_{ci} from when the resin was mixed, the ratio of infusion time at t_i to the initial infusion time t_0 was calculated, and equated to the ratio of cure viscosity to initial viscosity. The data at cure time $t_c = 180$ min for a flow front distance of 102 mm was neglected because this infusion took 39 minutes and the viscosity changes were deemed to be too large to be assumed constant over this time interval.

The plot of viscosity ratio against cure time is shown in Figure 29. An exponential curve fit was performed in MATLAB to calculate the β coefficient in Equation 15. β was determined to be equal to 0.0072 with a standard deviation of 0.0010 for the PT2712 resin system.

Figure 29: Relative increase in resin viscosity during cure

4.4.4 Verification of LIMS model

To verify the accuracy of the LIMS simulation and characterization of the preform and resin, an infusion was performed on a 0.26 m long 2 ply BGF 94107 carbon fibre layup. The location of the flow front was plotted with time using the method described in Section 4.4.2. Figure 30 shows the results of this experiment, as well as the LIMS simulation of flow front motion with and without the inclusion of the cure model. A mesh convergence study (shown in Appendix A) was performed, and it was found that elements of smaller than 19 mm caused the simulation to converge.

Figure 30: Simulation of 0.26 m infusion using LIMS model with and without compensation for resin cure

From Figure 30, it can be seen that the LIMS simulation of the infusion process is very accurate when cure effects are included in the model, especially when the flow front has passed approximately 0.15 m. The under-prediction of initial flow front speed was attributed to the following three sources of error:

- **Interaction between vacuum bag and the spiral flow line at the inlet:**

In the vicinity of the inlet spiral line, the vacuum bag lifted off the surface of the fabric due to the combination of low compaction pressure and bag tension caused by the presence of the spiral tube. As a result, resin accumulated above the fabric. This layer of resin above the fabric was able to flow with much less resistance than when in the fibre, and thus the fluid travels slightly more quickly than predicted over short distances.

- **Inaccuracies of the Kozeny-Carman equation at low fibre volume fractions:** For reasons discussed above, the decreased compaction pressure in the vicinity of the inlet line leads to fibre volume fractions below what was experimentally predicted. As discussed in Section 4.2.2, the Kozeny-Carman equation is only accurate above fibre volume fractions of approximately 0.2. This means that for short infusion lengths, a disproportionately high portion of the fluid within the preform will be outside of the range that the Kozeny-Carman coefficient can be considered constant, which could contribute to the inaccuracies of the simulation.
- **Inaccuracies of the empirical compaction model at low compaction pressures:** Due to the dead weight of the platen used in the compaction experiments, no compaction data could be obtained for very low compaction pressures. As a result, errors in the extrapolation of the exponential curve fit below the lowest compaction pressure that measurements were taken at could have further exaggerated the differences between the predicted and actual flow front motion over short infusion differences.

The simulation correlates quite well to the experimental data for longer infusions, however and it is more important for the model to be accurate for long infusions. This is because the LIMS model will primarily be used to predict infusion time and dry spot location, which can both be accurately predicted using a model that is most accurate at the end of an infusion. The LIMS simulations will tend to under-predict infusion times for objects less than 0.15 m in length, but dry spots and infusion time are much less of a concern for parts of this size, so the absolute accuracy of the simulation is not as important.

4.5 Development of resin flow model for mould emptying

To maximize compaction preform during VARTM infusions, it is standard practice to connect the resin inlet lines to vacuum lines after the mould has been completely filled. This will pull excess resin out of the resin-rich areas near the inlet, which maximizes compaction and fibre volume fraction, and minimizes thickness variations within the part. The effects of this step are shown below in Figure 31.

Figure 31: Comparison of part thickness at (a) the completion of mould filling, and (b) the completion of mould emptying with maximum compaction pressure. Plot generated from emptying simulation of 305 mm specimen described in Section 4.5.2.

From previous manufacturing trials it was noted that parts with a large distance between the inlets and outlets will exhibit greater thickness variations than parts with

more closely spaced inlets and outlets. This is to be expected because in order to fully compact the preform, the resin has a much further to travel in larger parts, and will therefore exhibit less motion.

A method for simulating the mould emptying process is developed below. The goal of this simulation is to determine the magnitude of the thickness variations that can be expected, and provide a method to optimize inlet and outlet location in mould design to minimize these thickness variations.

Developing a three-dimensional model would require code to generate three-dimensional meshes from a model. Furthermore, the simulation of a three-dimensional mould emptying would be quite computationally intensive, and could require significant time to complete. For simplicity, a mould emptying simulation was performed in only one dimension. This greatly simplifies the meshing procedure, and reduces computation time.

The one-dimensional simulation has the disadvantage that it can not be used to predict compaction at cure throughout a complex three-dimensional mould. It can, however, be used to predict the inlet-outlet separation at which thickness variations will be minimized. The results of this simulation can be applied to a complex three-dimensional part to optimize inlet and outlet placement with the goal of minimizing thickness variations. The following section details the development of the one-dimensional resin flow model, and the implementation of this model in MATLAB code to perform part emptying simulations.

4.5.1 Governing equation for one-dimensional resin flows

For one-dimensional flows where resin flow in the y and z directions can be neglected, an analytical expression for fluid motion was derived by Correia *et al.* [38] by combining Equation 2 with the continuity equation shown in Equation 17 below.

$$\frac{\partial h}{\partial t} = -\frac{\partial(u \cdot h)}{\partial x} \quad (17)$$

where h is local material thickness and t is time. The thickness can be related to fibre volume fraction using the following equation:

$$h = \frac{NS_d}{\rho v_f} \quad (18)$$

where N is the ply count, S_d is the fibre area weight, and ρ is the density of the fibre preform.

By combining Equations 2 and 17, the following partial differential equation describing resin flow can be derived:

$$\frac{\partial h}{\partial t} = \frac{1}{\mu} \cdot \left[\left(K \cdot \frac{\partial h}{\partial P} + h \cdot \frac{\partial K}{\partial P} \right) \cdot \left(\frac{\partial P}{\partial x} \right)^2 + h \cdot K \cdot \frac{\partial^2 P}{\partial x^2} \right] \quad (19)$$

Equation 19, a second order Partial Differential Equation (PDE), was used to model the mould emptying process. Developing an analytical solution for Equation 19 would be difficult, so MATLAB was implemented to compute a numerical approximation of the solution.

4.5.2 MATLAB simulation of mould emptying

To solve Equation 19 using MATLAB, the numerical PDE solver `pdepe` was used. To use `pdepe`, Equation 19 must be expressed in the form shown in Equation 20 [59].

$$C \left(x, t, P, \frac{\partial P}{\partial x} \right) \frac{\partial P}{\partial t} = x^{-m} \frac{\partial}{\partial x} \left(x^m F \left(x, t, P, \frac{\partial P}{\partial x} \right) \right) + S \left(x, t, P, \frac{\partial P}{\partial x} \right) \quad (20)$$

where $m = 0$ and the functions C , S and F are given by Equations 21, 22 and 23

respectively.

$$C = \frac{\mu_0 e^{a(t+t_i)}}{hK} \cdot \frac{\partial h}{\partial P} \quad (21)$$

where t_i is the fill time of a specimen of length L .

$$S = \left(\frac{1}{h} \cdot \frac{\partial h}{\partial P} + \frac{1}{K} \cdot \frac{\partial K}{\partial P} \right) \left(\frac{\partial P}{\partial x} \right)^2 \quad (22)$$

$$F = \frac{\partial P}{\partial x} \quad (23)$$

The previous three equations feature partial derivatives of h and K with respect to P . These partial derivatives were evaluated by combining Equations 18, 8 and 10 and are shown in Equations 24 and 25 below.

$$\frac{\partial h}{\partial P} = \frac{S_d N B}{\rho v_{f0} (P_{atm} - P)^B (P_{atm} - P)} \quad (24)$$

$$\frac{\partial K}{\partial P} = \frac{3k_0 (1 - v_{f0} (P_{atm} - P)^B)^2 B}{v_{f0} (P_{atm} - P)^B (P_{atm} - P)} + \frac{2k_0 (1 - v_{f0} (P_{atm} - P)^B)^3 B}{v_{f0}^2 ((P_{atm} - P)^B)^2 (P_{atm} - P)} \quad (25)$$

where $\frac{\partial h}{\partial P}$ and $\frac{\partial K}{\partial P}$ are both only a function of P as well as constant material properties.

A MATLAB script file was used to implement `pdepe`. Pressure was calculated as a function of x distance and time, where the spatial variable was discretized with a mesh of 100 nodes. The initial conditions and boundary conditions that were used are described in the following section.

4.5.3 Initial conditions and boundary conditions

The two nodes at each end of the mesh are both connected to the vacuum line, which gives rise to the following boundary conditions:

- $P(x, t)_{x=0} = 0$
- $P(x, t)_{x=L} = 0$

The initial state of pressure within the mesh is equal to the pressure distribution of the resin at the moment the flow front reaches the length L . This pressure distribution was determined from a LIMS simulation of an infusion of the same distance, and was input directly into the initial conditions of the solver. An example of the initial pressure state that was used is shown in Figure 32.

Figure 32: Pressure distribution between the inlet and outlet at $t = t_{full}$ from LIMS simulation

4.5.4 Results of mould emptying simulations

The simulation was run with total length L ranging from 0.152 m to 0.3048 m. It was assumed that the resin cured at $t = 180$ minutes, which is the published pot life of the PT2712 resin system [53]. The initial time t_i when the inlets were reversed was taken from the LIMS simulation of the flow front motion. The distribution of resin pressure over L during mould emptying was computed for each distance, and was used to compute h and v_f . The plot of pressure variation during mould emptying is shown in Figure 33.

Figure 33: Pressure distribution vs. time for simulation of 152 mm specimen

To evaluate the simulation results the values of P , h and v_f at resin cure were plotted for each infusion length, and are shown in Figures 34, 35 and 36 respectively. Each plot shows the average, maximum, and standard deviation of the ordinate variable.

Figure 34: Resin pressure at cure as a function of specimen length

Figure 35: Specimen thickness at cure as a function of specimen length

Figure 36: Specimen fibre volume fraction at cure as a function of specimen length

The plot of thickness variation as a function of part size (Figure 35) can be used to select an appropriate inlet/outlet configuration to minimize thickness variation. Furthermore, Figure 35 also gives an indication of the tolerances that can be expected for cured parts.

4.5.5 Comparison to experimental mould emptying

To experimentally validate the mould emptying model developed above, an infusion was performed on a short (0.152 m) and a long (0.254 m) flat rectangular specimen of 2-ply carbon fibre. Each infusion was run until the part was fully infused. At that point, the inlet line was attached to the vacuum pump to initiate resin emptying, and the part was allowed to cure under vacuum pressure. The thickness of the panel was

measured along its length with 25.4 mm spacing using calipers after cure, and was plotted against the relative distance between inlet and outlet. From the emptying simulation results, very little thickness variation should be observed in the short specimen, and a large increase in thickness in the centre of the long specimen should be observed. Figure 37 shows the thickness of the 0.152 m and 0.254 m specimens as predicted by the emptying simulation, as well as the measured thickness in the two test specimens.

Figure 37: Experimental thickness measurements of 0.152 m and 0.254 m specimens

The short specimen displayed some variation about the experimentally predicted line, but no net increase in thickness was observed and the thickness variations were attributed to non-uniformities within the carbon fibre preform. The simulation of the

short specimen predicts that there will be no significant thickness variations throughout the part.

The longer specimen, however, displayed a net increase in thickness between the inlet and outlet which could not be explained by natural variations within the fibres alone. When compared to the thickness variation predicted by the emptying simulation, these thickness variations are adequately explained by the incomplete resin emptying at cure. There are some discrepancies between the simulation and experimental thicknesses at $0.2 < d/d_0 < 0.4$ which could have been caused by local preform variations, or damage to the fibres during the layup procedure. Although the simulation was not able to exactly predict the thickness of the one-dimensional part at every location, the maximum thickness increase was still predicted with an error of only 1.3%

From this experiment, the mould emptying simulation developed above may not be able to exactly predict the final thickness at any given location throughout a part, but can be used to optimize the inlet and outlet placement to ensure that thickness variations are as small as possible. For example, for this particular preform permeability and resin cure cycle, the maximum thickness variation is 36.1% if the inlet is placed at 0.254 m from the outlet and a linear flow front is achieved. However, if the inlet is moved to 0.203 m from the outlet, the maximum thickness increase of the cured part is only 12.1%.

Chapter 5

A study of thickness variation, void content and strength in part corners

Manufacturing trials conducted by the LCC group at Carleton University have shown that resin-rich areas, increases in thickness, and void accumulation frequently occur in tight corners of parts made using the VARTM method. These defects are described in detail in Chapter 2. The following section examines the effects of corner compaction pressure on this common manufacturing defect, and a layup method designed to minimize thickness variations in corners is proposed. The variability of part thickness, void content, and strength was evaluated for the bagging technique currently used at Carleton, as well as for a novel bagging technique designed to reduce variability in part corners.

5.1 Causes of low compaction pressure in part corners

As the preform is compacted due to the application of vacuum pressure, the volume inside the vacuum bag is reduced. Inside corner features require the bag to stretch to fill the compacted shape. When the bag is not able to fully stretch into these corners,

the preform is not properly compressed in the vicinity of the corner. This is shown in Figure 38 (a).

Another possible cause of poor corner compaction was proposed by Flynn [60]. Flynn described how tension in the preform can cause the fibres to not be properly compacted against an inside corner edge in RTM infusions. This is shown in Figure 38 (b).

The loss of compaction pressure in part corners due to tension in the bag or preform is called bridging, and can lead to resin rich areas [61] as well as race-tracking during the infusion process. Lawrence *et al.* [62] investigated an automated resin delivery system to compensate for these curvature effects during infusion to prevent dry spots.

A third cause of variability in part corners was observed in manufacturing trials performed at Carleton; folds tended to develop when the preform was forced around a corner, and these folds would occasionally cause local corner thickness variations. This is shown in Figure 38 (c).

Figure 38: Three modes of corner thickness variability: vacuum bag tension (a), preform tension (b), and fibre wrinkling (c) (mould shown in black, fibre preform in light grey, and flexible vacuum bag in dark grey)

5.2 Experimental investigation of corner defects

In order to test the quality of three-dimensional parts, 90° L-channel coupons were manufactured using the VARTM method. The effects of the following three parameters on corner thickness, void content, and strength are examined through experiment:

- **Corner radius:** The radius of the part corner could affect the defects present within that corner. Corner radii of 1.6 mm, 3.2 mm, 6.4 mm, and 12.7 mm were tested to determine the effects of corner radius on manufacturing defects.
- **Inside or outside corner:** Whether the preform was located on the inner or outer surface of the corner mould potentially affect the presence of manufacturing defects. Coupons were manufactured with both inside and outside corners to examine this effect.
- **Bagging method:** Interactions between the vacuum bag and preform could potentially cause defects within corner parts. To investigate the effects of bagging technique a silicone bag, which replicates the method currently used by the LCC group; and a high-elongation Stretchlon bag, with silicone pressure enhancers in the corners were tested.

5.2.1 Bagging techniques

The following section describes the two bagging methods that were tested.

Re-usable silicone bag

Several complex parts have been successfully manufactured at Carleton University using custom silicone bags. Most notably, the GeoSurv II fuselage was infused using this method.

The reusable custom silicone bagging technique was developed as an alternative to one-time use vacuum bags and was designed to allow complex three-dimensional shapes to be manufactured with less variability and defects. Because each bag is custom made, it will be able to conform to details within the part with a high degree of accuracy. The disadvantage of using this method is that fabricating custom silicone bags is a time-consuming process, with expensive consumables.

Stretchlon bag with pressure enhancers

A method for bagging complex parts was developed using Stretchlon vacuum bagging material instead of the custom silicone bag. Stretchlon bag is made from a thermoplastic polyester elastomer from Hytrel [55, 56], and is designed to be extremely flexible, with a 600% elongation before rupture [57]. The high elongation will allow the Stretchlon bag to conform to complex geometries, without the use of a custom bag. In the new method, pressure enhancers were used in part corners to relieve any tension that may develop in the bag and cause defects associated with bag tension due to preform compaction (shown in Figure 38 (a)). Furthermore, these pressure enhancers will act as a caul plate, ensuring a smooth, uniform finish on the part corners. The goal of this method was to produce as high quality parts as the silicone bagging technique that has been used in past infusions, but with much less preparation time and cost. The placement of pressure enhancers in the layup is shown in Figure 39.

Figure 39: Location of pressure enhancers beneath vacuum bag

5.2.2 Test matrix

A test matrix shown in Table 6 was used to determine the effects of bagging method, corner type, and corner radius on part tolerances, void content, and strength. Parts made using both female and male moulds (inside and outside corners, respectively) were tested to eliminate the effects of fibre wrinkling on thickness measurements; outside corners will still have effects of wrinkling, but will not experience losses in compaction. Therefore, the effects of compaction pressure loss could be isolated by comparing inside corner measurements to those taken on the corresponding outside corner.

Bag type	Corner radius (mm)	Corner type	Test
Stretchlon bag	1.6	Inside	A16I
		Outside	A16O
	3.2	Inside	A32I
		Outside	A32O
	6.4	Inside	A64I
		Outside	A64O
	12.7	Inside	A127I
		Outside	A127O
Custom silicone bag	1.6	Inside	B16I
		Outside	B16O
	3.2	Inside	B32I
		Outside	B32O
	6.4	Inside	B64I
		Outside	B64O
	12.7	Inside	B127I
		Outside	B127O

Table 6: Experimental testing matrix used for corner test pieces

5.2.3 Design and manufacturing of the corner test specimen mould

To minimize the number of infusions required to manufacture all specimens in the test matrix, a mould was designed that can be used to manufacture parts with inside and outside corners of the four radii that are shown in Table 6. This allows every specimen in the test matrix to be made using a total of two infusions; one bagged using Stretchlon film with pressure enhancers, and the other using the re-usable silicone bag.

The mould is shown in Figure 40. A three-view diagram of the mould is shown in Appendix B. This mould contains inside and outside corners of various radii, and

has inlet and outlet channels machined into the surface. By machining the inlet and outlet channels directly into the mould surface, each infusion will have a consistent injection location which limits variability due to differences in part infusion.

Figure 40: Solid model of corner test part mould showing inlet and outlet placement, corner radii

Using the mould shown in Figure 40, a series of 90° corner test parts could be constructed. A solid model of a corner test part, along with its dimensions, is shown in Figure 41.

Figure 41: Solid model of corner test specimen

5.2.4 Selection of fibre layup

When selecting the fibre layup for the corner test parts, the following two requirements were considered:

1. The test layup must be representative of what will be used on components that will be constructed for the GeoSurv II. The following three GeoSurv II components were the focus of this research:
 - (a) The GeoSurv II fuselage was constructed out of 1-8 plies of woven carbon fibre, the majority being 1-3 plies [4]. These plies contained balanced combinations of $(0^\circ, 90^\circ)$ and $(45^\circ, -45^\circ)$ plies.
 - (b) The GeoSurv II hatch covers were constructed from 2 plies of woven carbon fibre with the following ply orientation: $[(0^\circ, 90^\circ), (45^\circ, -45^\circ)]$.

- (c) The GeoSurv II empennage will be constructed from 1-3 plies of woven carbon fibre.
- 2. The test layup must be thick enough that the effect of preform compaction on bag tension will be apparent; thin preforms will not display local thickness variations as prominently as thicker preforms.

A three-ply layup of BGF 94107 was selected with the following ply orientation: $[(0^\circ, 90^\circ), (45^\circ, -45^\circ), (90^\circ, 0^\circ)]$. This layup is representative of layups that have been used in the fuselage and hatch covers, as well what will likely be used on the empennage. Furthermore, it is thick enough that any thickness variations in corners will be apparent.

5.2.5 Manufacturing of custom silicone bag

A custom silicone bag was manufactured for the corner test mould with the CCBM method described in detail in 2.1.4. A manufacturing method was chosen for the silicone bag that replicates the method used by Mahendran [4] to construct the GeoSurv II fuselage. This was done by considering the following three processing parameters:

1. **Silicone moulding procedure:** When manufacturing the bag, three layers of carbon fibre were placed on the surface of the mould as a separator, and the silicone was formed on the carbon preform as opposed to directly on the mould. Custom bags made using the CCBM method are generally manufactured on top of the un-compacted fibre preform, and when vacuum pressure is drawn within the cavity, the bag will deform to fit the compacted shape of the part. This behaviour was replicated in the corner test parts by manufacturing the bag over a fibre layup.

2. **Bag thickness:** The bag was manufactured from three layers of silicone, with an embedded reinforcement mesh to add strength and toughness. This process is equivalent to that used in the GeoSurv II fuselage vacuum bag and was done to replicate the stiffness and flexibility of the GeoSurv II bag. P-45, a two-part silicone from Silicones Inc. was used for the bag material.
3. **Sealing method:** The void content of the final parts can be significantly affected by the quality of the bag seal. In order to replicate the sealing method used on the GeoSurv II fuselage, a layer of tacky tape was attached to the outer surface of the silicone bag, and sealed against the mould face. Flashbreaker tape was bonded around the edges on the top surface of the bag to allow the tacky tape to adhere to the bag.

The finished silicone bag is shown in Figure 42:

Figure 42: Custom silicone bag used to manufacture test parts

5.2.6 Pressure enhancers

The pressure enhancers were manufactured by moulding a thin strip of P-45 to the inside corners of the mould. Unlike the silicone bag, the pressure enhancers were manufactured directly against the surface of the mould, giving them a smoother surface finish. The finished pressure enhancers are shown in Figure 43:

Figure 43: Pressure enhancers used to manufacture test parts

5.3 Measurement of compaction pressure in part corners

Measurements of the compaction pressure applied to the preform by the vacuum bag were taken in corners of the GeoSurv II fuselage and the test mould. This was done to quantify the magnitude of compaction pressure loss due to bag tension, and

to determine if this loss of compaction pressure contributes to part defects. Force-Sensing Resistors (FSRs) were used to take pressure measurements during the infusion of the GeoSurv II fuselage, and a pressure-sensing film was used to take pressure measurements of the test mould corners.

5.3.1 Measurement of corner pressure during the GeoSurv II fuselage infusion

Two GeoSurv II fuselages have been manufactured by Mahendran using the CCBM method, the second of which was infused when this research was taking place in May 2012. This opportunity was taken to quantify the compaction pressure losses that can be expected in complex three-dimensional structures during infusion. To do this, nine FSRs were mounted underneath the vacuum bag at various distances from inside and outside corners, as well as in flat sections. Each corner was instrumented with a sensor at its center, as well as at 10 mm and 20 mm distances from the corner sensor. Pressure measurements were taken as vacuum pressure was drawn prior to the infusion.

FSR data acquisition (DAQ)

The resistance across an FSR is related to the force applied to the sensor head. By calibrating each sensor to determine the relationship between applied pressure and resistance, FRS can be used to measure force. Each FSR was connected to an Arduino Uno through a voltage divider, which converts the variable FSR resistance to a voltage. The Uno read the voltage output of the voltage divider as a value between 0 and 1024, and transmitted this value to a laptop which stored the data.

FSR calibration

To calibrate the FSRs, known weights were used to apply a pressure to the sensor face, and the resulting relationship between applied pressure and sensor reading was used to develop an empirical calibration curve. Figure 44 shows the calibration curve for the Interlink FSR400 [63] developed for the fuselage pressure experiment.

Figure 44: Calibration curve for FSRs used in fuselage experiment

Experimental setup

Each of the 9 FSRs were embedded in the silicone bag, and the bag was re-sealed with silicone (Figure 45 (a) and (b)). The bag seam was sealed with tacky tape, and the DAQ unit was turned on (Figure 45 (c)). Vacuum pressure was then drawn in the bag, and the compaction pressure was recorded as a function of time.

Figure 45: Fuselage pressure measurement setup showing FSR sensors under bag (a), the bag instrumented with sensors (b), and the data acquisition system (c)

Results of force measurements during GeoSurv II fuselage infusion

When vacuum pressure was drawn on the fuselage, the compaction force applied to the sensor electrical connections caused six of the nine FSRs to fail. However, the remaining three sensors were located in the center of an inside corner, at 10 mm from the corner center, and in a flat section. This allowed a profile of compaction pressure in the bag corner to be developed.

Figure 46 shows the results of the compaction pressure measurements taken during the GeoSurv II fuselage infusion.

Figure 46: Pressure variation measured under silicone bag during infusion of Geo-Surv II fuselage

The sensors in the flat section and 10 mm from the center registered approximately 20 kPa of pressure before the vacuum pump was turned on. This was attributed to the weight of the bag pressing against the face of the sensor. The flat section sensor also failed after approximately 23 minutes, but sufficient data to determine maximum compaction pressure was recorded before the failure occurred.

Table 7 shows the maximum pressure reached during the infusion as measured by the three functioning sensors. Also shown in Table 7 is the maximum vacuum pressure reached in the infusion as measured by a dial gauge connected to the vacuum pump.

Table 7: Maximum pressure recorded at three distances from 6.4 mm radius corner

Location	Maximum pressure (kPa)
Flat section	92.9
10 mm from corner	76.4
Corner center	29.4
Vacuum pressure (dial gauge)	96.0

The pressure measurements presented above show a significant drop in compaction pressure in the inside corner of the fuselage. This indicates that the silicone vacuum bag was not able to fill the corner and apply full pressure. It should be noted that the maximum compaction pressure measured by the flat section sensor was 92.9 kPa, whereas the vacuum pump registered 96.0 kPa of pressure. This discrepancy could have been caused by the pressure sensor failing before full compaction pressure was reached. Other possible sources of error are inaccuracies in the calibration of the pressure sensors, or a difference in pressure between the location of the dial gauge and the location of the FSR.

5.3.2 Measurement of corner pressure in the test mould

The pressure method presented above was found to be unreliable due to the frequent failure of the FSRs. For that reason, Pressurex Tactile Pressure Indicating Film was used for the test part pressure measurements. The pressure indicating film is a single-use pressure measurement device that changes colour under an applied load. The intensity of the colour change is proportional to the applied pressure, where a darker colour corresponds to higher applied pressure.

To determine the corner compaction pressure in the test mould, strips of the pressure indicating film were placed above the carbon fibre preform and below vacuum bag and pressure enhancers. Figure 47 shows the measured pressure using the Stretchlon bag with pressure enhancers. Figure 48 shows the measured pressure distribution using the silicone bag.

Figure 47: Pressurex film measurement for test part corners under Stretchlon bag

Figure 48: Pressurex film measurement for test part corners under silicone bag

A drop in corner pressure can be seen in figures 47 and 48 in the vicinity of the inside corners. The corner pressure drop is less pronounced in the measurement of the silicone bag, and takes place over a smaller area. There was also a local drop in compaction pressure along the edge of the pressure enhancers.

Occasionally, wrinkles formed in the pressure sensing film which prevented it from undergoing the colour change. These wrinkles would frequently form in the vicinity of corners.

The outside corners displayed very little variation in pressure using both the Stretchlon and silicone bags when compared to the flat sections. The variations that did exist were attributed to folds that formed in the pressure indicating film.

Corner radius did not appear to significantly affect the pressure gradient in the vicinity of the corner. Local variations were observed, but no patterns can be seen in the data.

5.4 Manufacturing of corner test parts

Three sets of corner test parts were manufactured for each bagging technique, for a total of 48 specimens. The corner test parts were then cut to the final shape with the dimensions shown in 41. Figure 49 shows an example of the layup and bagging method used when manufacturing the Stretchlon test parts.

Figure 49: Various layers used in carbon fiber layup (Stretchlon vacuum bagging method)

The yellow tacky tape used to seal the mould can be seen around the edges of this layup, and was placed between the bag and the mould. In the silicone bag layup, however, this tacky tape was placed on top of the bag and sealed against the mould face to replicate the method used on the GeoSurv II fuselage.

5.5 Presentation of data

When presenting the data gathered in the corner test experiments, the specimens were grouped in the following manner:

- By corner type and bagging method. Each group contained 12 specimens.
- By corner radius. Each group contained 12 specimens.
- By corner type, bagging method, and corner radius. Each group contained 3 specimens.

The average and standard deviation of thickness variation, void content, and strength for the specimens in each of these groups is presented in the following three sections. The error bars on each plot show one standard deviation.

5.6 Thickness variability in corner test parts

The thickness of each part was measured at various locations, and the effects of bagging type, corner type, and corner radius on thickness are presented below.

5.6.1 Measurement method

Digital calipers were used to take measurements at various distances from the midpoint of the corner of each part. Six measurements were taken in the flat sections of each specimen, far away from the corners. In the specimens with a 1.6 mm corner, one thickness measurement was taken at the midpoint of each corner due to the corner's small size. In every other specimen, four thickness measurements were taken at fixed locations around the part corner. The effects of bagging type, corner type, and corner radius are examined in the following sections.

5.6.2 Effects of corner type and bagging method on part thickness

Figure 50 shows the effect of corner type on the thickness measurements for each bagging type. The thicknesses are expressed as a percent increase compared to flat section measurements in Figure 50. These measurements show that in both the flat sections, and outside corners, the thickness of both the Stretchlon bag and silicone bag is quite close to what was predicted using Figure 24, although the parts made using the Stretchlon bag were slightly thicker than those made with the silicone bag. The standard deviation of thickness in both the flat sections and outside corners is not significantly affected by bagging type. The standard deviation was slightly higher in outside corners than in the flat section, which can be attributed to wrinkles forming in the preform.

The thickness measured in the inside corners, and the standard deviation of thickness was significantly higher in the inside corners for parts made using both the Stretchlon bag and silicone bag when compared to the measurements taken in the flat section. The parts made using the silicone bag displayed less thickness increase, and less variation in thickness than those made using the Stretchlon bagging system.

Figure 50: Thickness variation due to corner type and bagging method

Figure 51: Thickness variation due to corner type and bagging method (percent change from flat section measurements)

5.6.3 Effects of corner radius on part thickness

Figure 52 shows the average and standard deviation of thickness for the four different corner radii. Corners between 1.6 mm and 6.4 mm had similar standard deviations

and average thicknesses, although a decreasing trend was observed with corner radius. The 12.7 mm corners, however, had an average thickness that was equal to the theoretically predicted flat-panel thickness. The 12.7 mm corners also had a standard deviation of 0.135 mm, which is less than the flat section standard deviation of 0.146 mm. This implies that the thickness of the part in the 12.7 mm corner was not affected by the presence of the corner.

Figure 52: Thickness variation due to corner radius

5.7 Void content of corner test parts

The presence of void defects in each part was quantified using the method described below, and the effects of corner type, bagging type, and corner radius are presented.

5.7.1 Measurement method

Four different test specimens are shown in Figure 53. Specimens (a) and (c) contain no voids in the corner, but specimens (b) and (d) contain corner surface voids visible to the naked eye. When quantifying the part defects, the presence of a corner void, regardless of its size, was recorded. To assess the void content of each method, the fraction of parts containing a corner surface void of any size was calculated.

Figure 53: Corner test specimens that contain an (a) inside corner with no voids, (b) inside corner with small voids, (c) inside corner with a large void and (d) outside corner with no voids

5.7.2 Effects of corner type on part void content

The fraction of parts containing a corner void is shown in Figure 54 for different corner types and bagging methods. Parts containing outside corners had the lowest chance of containing a corner void, and this was not dependent on the bagging method.

A much higher fraction of parts containing inside corners were found to contain corner voids, and of the parts containing an inside corner, parts made using the silicone bag had a much higher chance of containing a corner void than those made using the Stretchlon bagging method.

Figure 54: Effects of corner type and bagging method on the fraction of parts containing a corner void

Even though the silicone bag was able to provide more compaction pressure in the inside corners, a higher fraction of parts made using this method contained a void. This suggests that compaction pressure is not the most significant factor when determining void content. This discrepancy could have been caused by a poor seal between the silicone bag and the mould. The silicone bag was sealed by placing the tacky tape outside the bag to mimic the method used on the GeoSurv II fuselage, and this method does not provide as good a seal as the traditional method of placing

the tacky tape underneath the bag. If more air was able to enter the bag and become trapped in the corners, this could have lead to the higher void content seen in the parts made with the silicone bag.

5.7.3 Effects of corner radius on part void content

Figure 55 shows the fraction of parts of the four different radii that contained a corner void. Parts containing a smaller radius were much more likely to contain a corner void, with the most significant decrease taking place between 1.6 mm and 3.2 mm. The 12.7 mm radius corners had the lowest likelihood of containing a corner void, at 18%.

Figure 55: Effects of corner radius on the fraction of parts containing a corner void

5.8 Strength testing of corner test parts

A four-point bend apparatus was used to test each part to failure. The following section describes the destructive testing method used, and presents the effects of corner type, bagging type, and corner radius on part strength.

5.8.1 Experimental setup

A four-point bend apparatus was used to determine the strength of the corner test parts through destructive testing. The experimental apparatus and testing method were based on ASTM D6415/D6415M-06a^{e1} [64], a standardized method of determining the curved beam strength and interlaminar strength of layered composites.

The ASTM standard method was not replicated exactly, and the following deviations were made in the geometry of the specimens and apparatus:

- The ASTM test method requires that the test specimens have a thickness between 2-12 mm, which would necessitate a layup of more than three layers. The current layup was selected to be representative of the GeoSurv II fuselage, empennage, and avionics hatch, and it was deemed more important to match the layup of these components than replicate the ASTM standard exactly.
- The ASTM standard method requires that the test specimens have straight legs that are 90 mm or longer but the milling machines available at Carleton limited the dimensions of the mould used to make the test parts. The central cut in the corner test part mould (shown in Figure 40) could not be manufactured with the required depth of 90 mm so scaled down parts were constructed. The four-point bend apparatus used in the strength testing was made smaller than what is required in the ASTM standard method to meet the manufacturing constraints of the test specimens. Care was taken to ensure that the relative separation of

the four load application points matched that of the ASTM standard apparatus.

- A corner radius of 6.4 mm was required to meet the ASTM standard method.

It was the goal of this testing to examine the effects of a range of corner radii on part strength, so this requirement was neglected.

The goal of the strength testing was not to determine a strength value to predict ultimate strength for component design, but rather to quantify the relative strengths between corner parts made using various manufacturing methods. For that reason, it was deemed that the deviations made from the ASTM standard method for determining curved beam strength and interlaminar strength were acceptable, but should be taken as a comparative study only.

Figure 56 shows the four point bend apparatus used in this research. The dimensions of the upper and lower bearing fixtures are shown in Appendix C. An MTS 810 load frame with a 25 kN capacity was used under displacement control to conduct the testing. The load cell that was used had an accuracy of ± 12.5 N.

Figure 56: Four point bend fixture used to test composite corner specimens

5.8.2 Results

Each part was tested to failure using the apparatus described above. The failure load was determined from the initial onset of delamination. Figure 57 shows a specimen

being tested before (a) and after (b) delamination has occurred. No damage to the parts were observed at the location where the loading points contacted the specimens.

Figure 57: Corner test specimen before (a) and after (b) failure

The load at which initial delamination occurred could be determined from the load-displacement plot for each test. Figure 58 shows an example of a load-displacement plot generated during strength testing. When two layers delaminate, the load-carrying capacity of the specimen will suddenly decrease. In the three-ply layup, there are two interfaces that will experience delamination during testing, giving rise to the saw-tooth pattern seen in Figure 58, where each sudden drop in the load-carrying capacity corresponds to the delamination of an interface. The failure load of each specimen was taken as the maximum load reached immediately before the first delamination.

Figure 58: Example of force-displacement curve for destructive testing of corner test parts (specimen B1270-2)

Failure load

The the failure load of each specimen was determined using the method described above. Figure 59 shows the average failure load for each corner radius, bagging technique, and corner type. Figure 60 shows the average failure load for each corner type and bagging method. Figure 61 shows the average failure load for each radius.

Figure 59: Average failure load for each bagging method, corner type and corner radius

Figure 60: Average failure load for each bagging method and corner type

Figure 61: Average failure load for each corner radius

Curved beam strength

The curved beam strength is defined as the maximum moment per unit width supported by the test specimen before failure, and is calculated using Equation 26 [64].

$$CBS = \frac{M}{w} = \left(\frac{F}{2w \cos(\phi)} \right) \left(\frac{d_x}{\cos(\phi)} + (D + t_s) \tan(\phi) \right) \quad (26)$$

where M is the applied moment, w is the specimen width, F is the applied load, ϕ is half the overall angle between specimen loading arms, d_x is the horizontal separation of the top and bottom cylinders measured from their centerlines, D is the diameter of the cylindrical rollers, and t_s is the specimen thickness.

When solving Equation 26, the value of ϕ at failure is used. This can be calculated

using the vertical distance between the cylindrical loading bars as shown in Equation 27 [64]:

$$d_y = d_x \tan(\phi_i) + \frac{D + t_s}{\cos(\phi_i)} - \Delta \quad (27)$$

where d_y is the vertical separation between cylindrical rollers at failure, Δ is the vertical deflection of the test specimen at failure, and ϕ_i is the initial value of ϕ with no vertical deflection.

The value of d_y can then be used to calculate the value of ϕ at failure using Equation 28 [64]:

$$\phi = \sin^{-1} \left(\frac{-d_x(D + t_s) + d_y \sqrt{d_x^2 + d_y^2 - D^2 - 2Dt_s - t_s^2}}{d_x^2 + d_y^2} \right) \quad (28)$$

The curved beam strength of each test specimen was calculated using the method described above. Figure 62 shows the average curved beam strength for each corner radius, bagging technique, and corner type. Figure 63 shows the average curved beam strength for each corner type and bagging method. Figure 64 shows the average curved beam strength for each radius.

Figure 62: Average curved beam strength for each bagging method, corner type, and radius

Figure 63: Average curved beam strength for each bagging method and corner type

Figure 64: Average curved beam strength for each corner radius

Interlaminar strength

Lekhnitskii [65] developed solutions for the radial stress within a anisotropic, homogeneous curved beam subject to a pure bending load. A formulation of Lekhnitskii's equation that can be used to calculate the maximum interlaminar stress at failure was developed by Kedward *et al.* [66], and is shown in Equation 29.

$$\sigma_r = -\frac{CBS}{r_o^2 g} \left[1 - \frac{1 - \rho^{\kappa+1}}{1 - \rho^{2\kappa}} \left(\frac{r_m}{r_o} \right)^{\kappa-1} - \frac{1 - \rho^{\kappa-1}}{1 - \rho^{2\kappa}} \rho^{\kappa+1} \left(\frac{r_o}{r_m} \right)^{\kappa+1} \right] \quad (29)$$

where r_i and r_o are the inner and outer radii of the test specimen, respectively. The values of ρ , κ , g and r_m can be solved using Equations 30, 31, 32 and 33, respectively:

$$\rho = \frac{r_i}{r_o} \quad (30)$$

$$\kappa = \sqrt{\frac{E_\theta}{E_r}} \quad (31)$$

$$r_m = \left[\frac{(\kappa + 1)(1 - \rho^{\kappa-1})\rho(r_i r_o)^\kappa}{(\kappa - 1)(1 - \rho^{\kappa+1})} \right]^{\frac{1}{2\kappa}} \quad (32)$$

$$g = \frac{1 - \rho^2}{2} - \frac{\kappa}{\kappa + 1} \frac{(1 - \rho^{\kappa+1})^2}{1 - \rho^{2\kappa}} + \frac{\kappa \rho^2}{\kappa - 1} \frac{(1 - \rho^{\kappa-1})^2}{1 - \rho^{2\kappa}} \quad (33)$$

where E_θ and E_r are the laminate stiffness in the radial and tangential directions, respectively, and were determined from composite lamina analysis [67]. The properties of the fibre and matrix material used in the test parts are shown in Appendix D. Equations 34 [67] were used to calculate the radial stiffness of the specimens.

$$E_r = \frac{E_f E_m}{E_m v_f + E_f (1 - v_f)} \quad (34)$$

To use Equation 29, the corner test pieces were assumed to be homogeneous. This could be done because although the corner test specimens had multiple ply orientations, the bending stiffness of the part was dominated by the (0°, 90°) plies located on the top and bottom faces of the parts. Therefore, the central layer of (45°, -45°) fabric did not cause significant deviations from the interlaminar stress predicted using the homogeneous assumption. The tangential stiffness of the specimens could therefore be approximated as E_1 of the outer plies. The tangential stiffness of the parts was calculated using Equation 35. Because each outer ply contained both 0° and 90° plies, the average of the two stiffnesses was used.

$$E_{\theta} = \frac{E_1 + E_2}{2} = \frac{1}{2} \left(\frac{E_f E_m}{E_m v_f + E_f (1 - v_f)} \right) (E_f v_f + E_m (1 - v_f)) \quad (35)$$

The interlaminar strength of each test specimen was calculated using the method described above. Figure 65 shows the average interlaminar strength for each corner radius, bagging technique, and corner type. Figure 66 shows the average curved beam strength for each radius.

Figure 65: Average interlaminar strength for each radius, corner type, and bagging method

Figure 66: Average interlaminar strength for each radius

Figure 65 shows an unexpected trend; the 1.6 mm and 3.2 mm radius specimens had a much higher interlaminar strength than those with a larger radius corner. The 1.6 mm radius specimens in particular had an extremely high interlaminar strength and variation. Upon examination of Equation 29 it was found that the interlaminar strength of parts was extremely sensitive to radius when parts had a large ratio r/t . Considering this, the large interlaminar strength found in the 1.6 mm radius specimens containing an inside corner was likely because the actual radius of the as-manufactured mould deviated from the as-designed radius due to mould finishing procedures. Slight differences between the actual and theoretical radii of these parts would significantly affect the interlaminar strength calculated using Equation 29. This suggests that tighter control is needed over part radius and thickness to accurately determine the interlaminar strength for parts with radii less than 3.2 mm.

Figure 67 shows the average interlaminar strength for each corner type and bagging method, excluding the 1.6 mm radius data points, which were neglected due to the reasons discussed above.

Figure 67: Average interlaminar strength for each bagging method

Effects of the presence of a corner void on specimen strength and variability

The average failure strength, curved beam strength, and interlaminar strength was computed for specimens with and without voids, and is shown in Table 8. The standard deviation of each value is shown in brackets.

Table 8: Effect of corner voids on part strength (standard deviation shown in brackets)

Parameter	Voids	No voids	Percent change
Failure strength (kN)	0.84 (0.45)	0.85 (0.33)	1.4% (-37.3%)
Curved beam strength (kN)	0.091 (0.037)	0.094 (0.027)	3.4% (-35.9%)
Interlaminar strength (MPa)	23.2 (13.5)	16.9 (8.1)	-27.2% (-65.6%)

Parts containing a 1.6 mm radius were neglected when calculating the average interlaminar strength for the reasons discussed in Section 5.8.2.

Discussion of the strength testing results

The average failure strength and curved beam strength, shown in Figures 60 and 63 respectively, is higher for inside corner parts than those containing an outside corner. This was attributed to the fact that inside corners tended to have an increased thickness when compared with outside corners, and would therefore be able to support a higher bending moment before failure. Furthermore, the standard deviations of failure strength and curved beam strength were larger for inside corner specimens, which was likely a result of larger thickness variations within these parts. These two results suggest that the failure load and curved beam strength of the specimens was quite dependent on corner thickness. The interlaminar strength was found to be higher for inside corner specimens than outside corner specimens. However, the standard deviation of interlaminar strength was extremely high for inside corner specimens, suggesting a large amount of inter-specimen variability in inside corner parts.

Bagging method had little effect on the failure load of outside corner parts, but inside corner specimens failed at a higher load, and had less variability if they were

manufactured using the silicone bagging technique. Parts made with both bagging techniques had similar curved beam strengths, and the slight difference between the two averages was much smaller than the standard deviation of the measurements. Therefore, the results do not indicate a relationship between bagging method and curved beam strength. Outside corner parts made using a silicone bag had a slightly higher interlaminar strength than those made using the Stretchlon bagging technique. However, it was found that parts made using the Stretchlon bag had much lower variability than those made using the silicone bag. This suggests that the quality of the bond achieved between the plies was much more consistent when the Stretchlon bagging technique was used; a result that was likely caused by the lower void content in Stretchlon parts.

It was expected that parts with a smaller radius would have a higher failure load and curved beam strength; these parts tended to be thicker and should therefore have a larger second moment of area, allowing them to support a larger applied load. However, a positive correlation between strength and corner radius can be seen in Figures 64 and 61. This is likely because smaller radii corners had more local variations in thickness due to poor compaction, and these local defects constitute a greater percentage of the total part size.

Unexpectedly, the presence of a corner void only slightly increased the average failure strength and curved beam strength. This was likely because the defects were observed to primarily accumulate on the surface of the corner, whereas the specimens failed between the layers of fabric. It is possible that the bond between plies within the specimens was not significantly affected by the presence of the corner void.

Corner voids did have a large effect on the standard deviation of the measured part strengths. The increase in scatter is to be expected, because the presence of a void introduces complicated and unpredictable stress concentrations into the matrix, that act as sites for crack initiation.

5.9 Effects of bagging method and corner radius on part quality

Loss of compaction pressure was proposed as a possible cause of the thickness variations and void content commonly found in parts made using a VARTM infusion. The compaction pressure was experimentally measured in various locations in preforms containing complex, three-dimensional shapes, and found to decrease by as much as 68% in inside corners, suggesting that compaction pressure loss is a significant cause of manufacturing defects.

The effects of the presence of a corner on part strength, thickness, and void content were studied for two different bagging techniques. The radius of the corner was found to have a significant effect on thickness variations, void content and strength. By far the greatest increase in performance occurred in the 12.7 mm radius specimens. However, it will not always be feasible to incorporate such a large radius into all composite designs, and significant improvements in compaction pressure, void content, and strength were present in radii 3.2 mm and larger.

Parts manufactured using the silicone bag tended to be stronger, achieve better compaction, and have less variability than those made using the Stretchlon bag and pressure enhancers. However, parts manufactured using the Stretchlon bagging technique had a much lower likelihood of containing a void in the vicinity of the corner. This was attributed to the ability of the Stretchlon bag to form a better seal against the mould surface, allowing less air to enter the cavity. The presence of the void itself introduced greater variability in the strength of the part, and when designing a composite structure, reducing part-to-part variation can be more important than maximizing average performance.

Based on these experiments, the silicone bagging technique will, in general, produce parts with higher strength and tighter tolerances. However, this technique tends

to lead to voids in small part details, so if a high-quality surface finish free of voids is required, the Stretchlon bagging technique with pressure enhancers is a more appropriate solution.

Chapter 6

Optimization of VARTM infusion processing parameters for two components of the GeoSurv II

In Chapter 4, a simulation tool was developed that can be used to reduce thickness variation and prevent dry spots during VARTM infusions. In Chapter 5, causes of common VARTM manufacturing defects were studied, and a novel bagging technique was tested to reduce the occurrence of these defects. In the following chapter, these two techniques are implemented to optimize the manufacturing of two GeoSurv II components; the mission avionics hatch and the inverted V-empennage. These two examples illustrate how the techniques developed to optimize processing parameters can be used to improve the quality of VARTM parts.

6.1 Infusion of GeoSurv II mission avionics hatch

The GeoSurv II fuselage has openings to access the flight avionics, mission avionics, and fuel bay. Each one of these openings is covered by a hatch, which acts as an aerodynamic fairing and protects the contents of the fuselage. The mission avionics hatch, shown in Figure 68, was manufactured by the 2012-13 GeoSurv II Structures team,

and was chosen to test the processing parameter optimization methods developed in this research.

Figure 68: GeoSurv II fuselage and hatches [68]

The mission avionics hatch was chosen as a test part for two reasons: it contains tight inside corners which must be manufactured without defects to ensure a smooth surface finish, and is large enough that the infusion process needed to be simulated to prevent dry spots and maximize compaction.

The mission avionics hatch is a thin shell part that was made from a $[(0^\circ, 90^\circ), (45^\circ, -45^\circ)]$ layup of BGF 94107 carbon fibre fabric using a VARTM infusion. The following sections describe the optimization performed on the manufacturing processing parameters, and the results of the infusion.

6.1.1 Selection of infusion technique

When optimizing the infusion processing parameters of the mission avionics hatch, an infusion technique was chosen based on the following three requirements:

1. The materials and manufacturing cost of the hatch shall be reduced as much as possible:

- Justification of requirement: The mission avionics hatch is not a highly loaded component, and does not contribute significantly to the overall weight of the GeoSurv II as it is primarily an aerodynamic fairing. Furthermore, the hatch itself is not a mission-critical component, and its failure will not lead to loss of functionality of any vital aircraft systems (although the attachment points to the fuselage are much more critical). For these reasons, cost is the driving design factor, not performance.
- Selection of optimal technique: Stretchlon bag costs \$0.68/m², and will require approximately \$2.50 of silicone to construct the pressure enhancers [69]. A silicone bag costs approximately \$100/m² and requires Omega flow lines which cost approximately \$30/m [69]. Furthermore, the silicone bagging method has additional associated labour costs, which are discussed below.

2. The infusion setup shall be fast and easy:

- Justification of requirement: The bottom avionics hatch is not the only component that was manufactured by the 2012/13 GeoSurv II Structures team; all three hatches shown in Figure 68 were infused. It was required to minimize the manufacturing time of the hatches so the team could focus on more mission-critical components of the UAV.

- Selection of optimal technique: The construction of a silicone bag is a multi-step process requiring three layers of silicone, a layer of mesh reinforcement, and the placement and construction of flow channels and inlets. Between each step, the silicone must be allowed to cure. Mahendran found that manufacturing the silicone bag for the GeoSurv II fuselage required 15 hours of labour [4]. The construction of silicone pressure enhancers can be completed in a single step, and the sealing procedure of the Stretchlon bag is simpler than that of the silicone bag.

3. The hatch shall have a high-quality finish on its outer surface:

- Justification of requirement: The purpose of the mission avionics hatch is to direct airflow around the underside of the fuselage with little drag, and therefore it is important to have as smooth a surface finish as possible on the outer surface. The hatch infusion process should create a smooth outer mould line, with little or no finishing steps required before painting.
- Selection of optimal technique: Both the silicone and Stretchlon bagging techniques can be used with a female mould to give a high-quality surface finish. However, several tight inside corners are present in the hatch, and the manufacturing process should eliminate the formation of voids in these corners to minimize part finishing time. The use of Stretchlon bag with pressure enhancers has been shown to reduce voids present in part corners when compared to the silicone bagging technique, allowing a higher quality surface finish to be obtained with fewer finishing steps before painting.

Based on the requirements outlined above, the Stretchlon bagging film and silicone pressure enhancer method is best suited to be used on the hatch due to its low cost, fast setup time, and low likelihood of corner defects developing on the outside of the part.

6.1.2 Design of mould

To meet the requirement for a smooth outer surface finish, a female mould was used to manufacture the mission avionics hatch. The hatch was machined from a laminated block of Medium Density Fibre (MDF) board, and was then sealed and polished to achieve a good surface finish. The machining, sealing, polishing, and waxing procedures used on the mission avionics hatch mould are described in Appendix E. A three-view drawing of the mission avionics hatch is shown in Appendix F. Figure 69 shows the mould used to manufacture the mission avionics hatch.

Figure 69: MDF female mould of mission avionics hatch

The mission avionics hatch contains two sharp inside corners, shown in Figure 70. As large a radius as possible was chosen for these corners, as this was shown to reduce

thickness variability, minimize void content, and improve strength. Corners with a radius of 12.7 mm have the best performance, but it was decided that a corner this large would disrupt airflow over the fuselage, so a radius of 6.4 mm was chosen. The solid model of the mission avionics hatch, with the two 6.4 mm corners highlighted in red, is shown in Figure 70.

Figure 70: Solid model of mission avionics hatch showing tight corners on fore and aft faces

6.1.3 LIMS simulation of mission avionics hatch infusion

The infusion of the mission avionics hatch was simulated using the VARTM LIMS simulation developed in Chapter 4. The simulations were used to select an optimal resin injection scheme that minimizes fill time and thus thickness variation, as well as prevents dry spots. The following section describes the iterations used to select an optimal injection scheme.

Modelling and meshing the mission avionics hatch

An initial solid model of the mission avionics hatch was developed by Mahendran [4], and was updated to include a 5° draft angle and 6.4 mm corner radius on the fore and aft faces. The mould has an axis of symmetry along the length of the fuselage, so only the right half of the hatch was modelled. A mesh of 15 mm triangular elements

was generated using the ABAQUS 6.10 meshing tool. The meshed half of the mission avionics hatch is shown in Figure 71.

Figure 71: Triangular mesh used for simulation of mission avionics hatch

Iteration 1

When deciding on the inlet and outlet port location, an initial setup with four inlets and three outlets was chosen as a starting point. The inlets were distributed around the outer edge of the hatch, and the outlets were evenly spaced along the central axis of the mould. Figure 72 shows this injection scheme, as well as the simulation results. The initial iteration resulted in only 40.2% of the mould being filled after the resin cured at 10800 s.

Figure 72: LIMS simulation of hatch infusion (1st iteration)

Iteration 2

In the first iteration, the fluid flow front expanded radially outward from each injection port. However, when a linear flow front is achieved, fluid motion can be up to ten times faster than when the resin expands outward from a single point [52]. For the second iteration, several more inlets were added around the outside of the mould in an attempt to achieve a linear flow front. The results of the second simulation are shown in Figure 73. Although this inlet placement scheme performed better than Iteration 1, it still only resulted in 79.7% of the mould being filled after 1800 s.

Figure 73: LIMS simulation of hatch infusion (2nd iteration)

Iteration 3

For the third iteration, a spiral flow channel was placed around the edge of the hatch to create a linear flow front. Spiral flow channels allow resin to quickly flow along their length with little pressure losses, but also allow resin to be infused into the preform through slits in the channel walls. The results of the third simulation are shown in Figure 74. A linear flow front developed due to the spiral flow lines, and as a result, the hatch was fully infused after 3385 s.

Figure 74: LIMS simulation of hatch infusion (3rd iteration)

Because this inlet placement strategy led to the complete infusion of the hatch long before the resin cured, and an approximately linear flow front was generated, this method was chosen to infuse the mission avionics hatch. The following section presents the results of this infusion.

6.1.4 Infusion of mission avionics hatch

The flow line placement scheme for the bottom hatch infusion was selected based on Iteration 3 of the hatch simulations. The PT 2712 resin system was used for the infusion. Pressure enhancers for the fore and aft corners were manufactured using P-45 silicone. Spiral flow line was placed around the edge of the hatch, and resin inlets and outlets were placed in locations determined from Figure 74. The hatch infusion setup is shown in Figure 75.

Figure 75: Setup used for hatch infusion showing location of inlets and outlets

Figure 76 shows a comparison between the experimental and simulated flow front position during infusion.

Time	LIMS (3385 s)	Infusion (5940 s)
3 min
10 min
20 min
30 min
45 min
55 min

Figure 76: Experimental and simulated front motion during hatch infusion

The LIMS simulation predicted the hatch would take 3385 s to infuse, however the actual infusion of the hatch took 5940 s to complete. Figure 76 shows that the simulated and predicted flow front location match quite closely for the first 30 minutes

of the infusion. However, the resin flow front slowed down considerably between 30 and 45 minutes when it reached the two outer outlets. This was attributed to the fact that the two outlet lines removed a significant amount of resin from the mould during the infusion. This resin would have otherwise continued to flow through the fibre bed and advanced the flow front. The model of outlets in LIMS does not account for the removal of resin in this manner, so as a result it under-predicted the infusion time due to these effects.

Although the LIMS simulation did not exactly predict the fill time of the part, it was still an effective tool for optimizing inlet location - three iterations of inlet placement were required to achieve full infusion. Future improvement of the resin outlet model within the LIMS simulation could improve the accuracy of the model. Ideally, by recognizing the effect that outlets have on flow front motion, the two outlets could have been removed to prevent them from removing resin from the flow front and slowing down the infusion. This would improve the simulation accuracy and further reduce infusion time.

The finish on the outer surface of the hatch after de-moulding was quite smooth. Because a female mould was used, little preparation work needs to be done before the hatch is painted. Also, only minor voids were found in the tight corners, and little filler will be required to achieve a smooth hatch. The mission avionics hatch after de-moulding is shown in Figure 77.

Figure 77: GeoSurv II mission avionics hatch after de-moulding

6.2 Infusion setup of GeoSurv II empennage

A new inverted V-empennage was designed by the 2012/13 GeoSurv II Structures team as a replacement for the current GeoSurv II U-empennage. The new tail was designed to take advantage of weight savings resulting from composite manufacturing techniques developed by the LCC group, as well as an aerodynamic efficiency increase associated with V-tail designs [70] when compared with U-tails.

As of the completion of this research, the design of the inverted V-empennage has been finished, and the foam core material has been cut. It is expected that the manufacturing of the empennage will be completed during the summer of 2013.

The V-empennage design will be made using a foam core design with a composite skin. The entire empennage (excluding control surfaces) will be manufactured in a single step infusion using the Mouldless VARTM method. The empennage design is

shown in Figure 78.

Figure 78: GeoSurv II inverted V tail empennage design

6.2.1 Servo mounting plates

The empennage contains four aluminum servo mounting plates that will be mounted the carbon fibre skin in rectangular recesses on the surface of the airfoil. Figure 79 shows an exploded view (a), and cross section view (b) of the empennage with servo mounting plate. The relevant dimensions of the plate are shown in Appendix G.

Figure 79: Servo mounting plate shown in (a) exploded view and (b) cross section view

Care must be taken when manufacturing the empennage to ensure that defects in the carbon fibre skin do not prevent these plates from fitting in the recesses cut in the foam.

6.2.2 Selection of infusion method

The GeoSurv II empennage is a mission-critical component, as any failure in the empennage structure will likely result in a loss of aircraft. Furthermore, the empennage is a large component that is very expensive to re-manufacture if it is not infused properly on the first try. For these reasons, it is important to optimize the infusion process as much as possible to guarantee that a high-quality part will be produced in the first infusion.

When selecting the bagging method for the infusion, the following four requirements were considered:

1. The infusion method shall achieve high fibre compaction:

- Justification of requirement: The GeoSurv II currently requires 11 lbs of ballast in the nose landing gear to ensure the center of gravity is in the proper location. It is crucial that the weight of the empennage be minimized, as this will allow additional ballast to be removed from the nose, further magnifying weight savings.
- Selection of optimal technique: The interactions between the Stretchlon bag and the fibre reduces permeability and inhibit fluid flow, which reduces the amount of resin that can be removed during resin emptying. However, parts bagged with silicone have a higher permeability, and thus will have a lower weight after the excess resin is pulled from the preform.

2. The finished part shall have high dimensional tolerances on the boom

interface and servo mounting locations:

- Justification of requirement: The empennage is required to interface with the two tail booms, as well as with the servo mounting brackets. Both of these components have already been manufactured, so the dimensional tolerances on the outer mould line of the empennage need to be high enough to interface with these existing components.
- Selection of optimal technique: In Chapter 5, the silicone bag was shown to have a lower thickness variation in both corners and flat sections when compared to the Stretchlon bagging method.

3. The infusion method shall achieve a smooth outer surface finish with few additional finishing steps:

- Justification of requirement: The empennage will be manufactured with the vacuum bag on the outer surface of the mould, so the surface created between the bag and the carbon must be of a high quality. The number of additional steps required to prepare the empennage for painting should be minimized, as these add time to the manufacturing process and weight to the finished part.
- Selection of optimal technique: To achieve a smooth finish on the outer surface of the empennage, distribution medium should be avoided. This limits the use of the Stretchlon vacuum bag, because the empennage is a large component that will likely not be filled without distribution medium due to the reduced preform permeability caused by the Stretchlon bag. However, the silicone bag allows resin to flow more quickly through the part, and can have resin distribution channels moulded into its surface, which further improves resin flow.

The silicone bagging method is the best solution to meet the above requirements, as it is able to achieve higher fibre compaction, with less variability when compared to the Stretchlon bagging method. The additional costs and time associated with manufacturing the custom silicone bag are justified as the empennage is a mission-critical component that must be manufactured right the first time.

6.2.3 Use of resin distribution channels to reduce infusion time

A solution to achieve fast resin flow without the use of distribution medium was proposed by Mahendran [4], who used a network of resin distribution channels built into the silicone bag to reduce infusion time in the GeoSurv II fuselage. The channels were formed by embedding 3.2 mm wax cylinders into the silicone during bag manufacturing which are removed after the silicone cures to leave cylindrical channels throughout the bag. The effect of resin distribution channels on resin flow during the infusion of the GeoSurv II fuselage is shown in Figure 80.

Figure 80: Resin distribution channels used to reduce infusion time of GeoSurv II fuselage

Figure 80 shows how resin moved preferentially through the channels embedded in the silicone bag. The presence of these channels significantly reduced fuselage infusion time.

Resin distribution channel spacing

The spacing between individual channels significantly affects their performance. For example, if the channels are spaced too far apart, the resin will have a further distance to travel, and dry spots could occur. Furthermore, a large channel spacing will not allow the excess resin to be fully removed during the resin emptying phase, and excessive thickness variations could occur, with a corresponding increase in part weight. However, too many resin distribution channels should be avoided as they can occasionally lead to ridges on the finished surface which must be machined out, or covered with filler. Ideally, the channels will be spaced as far apart as possible while

still allowing for excess resin to be removed from the part during the resin emptying phase of the infusion.

An optimal resin distribution channel spacing was determined using the resin emptying simulation developed in Chapter 4. The initial resin pressure distribution at the completion of infusion between the channels can be determined from the distribution of flow fronts meeting in the middle of two channels (shown in Figure 81).

Figure 81: Pressure distribution between the resin distribution channels at $t = t_{fill}$

The preform pressure distribution was determined for resin distribution channel separations between 0.20 m and 0.61 m using the MATLAB emptying simulation. A two-ply layup of BGF 94107 was assumed for the empennage skin. Figure 82 shows the change in pressure distribution between resin distribution channels during the resin emptying process.

Figure 82: Change in pressure distribution due to mould emptying between two resin distribution channels (0.30 m channel separation)

Figures 83, 84 and 85 show the effects of channel separation on resin pressure, thickness, and fibre volume fraction respectively.

Figure 83: Empennage resin pressure at cure as a function of resin distribution channel separation

Figure 84: Empennage skin thickness at cure as a function of resin distribution channel separation

Figure 85: Empennage fibre volume fraction at cure as a function of resin distribution channel separation

Figure 84 shows that part thickness and variability can be minimized with channel separations up to approximately 0.30 m. Separations larger than this lead to significant increases in part thickness and variability. For that reason, a resin distribution channel separation of 0.30 m was chosen for the empennage custom silicone bag which is slightly larger than the 0.20 m channel separation used by Mahendran when constructing the fuselage silicone bag [4].

6.2.4 Design of servo mounting bracket cutout

The recess that will be machined into the foam core to hold the servo mounting bracket must be sized to allow for the thickness of the carbon fibre skin. This recess will be over-sized during machining to accommodate for variation in the thickness of

the carbon fibre. Two causes of skin thickness variability were considered: variation due to incomplete emptying, and part-to-part variability.

The variation due to incomplete emptying was incorporated by assuming the skin will have an average thickness equal to the maximum predicted thickness with a 0.30 m flow channel separation. The part-to-part variability was characterized in Chapter 5 for a 3-ply layup of carbon fibre. It was assumed that the variability in the two ply layup can be approximated as two thirds the standard deviation for the 3-ply layup in a flat section. An additional thickness of two standard deviations was added to the recess size to allow for part-to-part variation in the thickness. The value of two standard deviations was chosen because 95% of the carbon fibre will have a thickness less than two standard deviations above its mean value.

Equation 36 was used to calculate the thickness increase d to be added to the outer dimensions of the servo mounting plate to account for the thickness of the carbon fibre when sizing the plate cavity to be cut in the foam.

$$d = t_{max} + 2 * SD_{2ply} \quad (36)$$

where t_{max} is the maximum thickness of the preform predicted by the emptying simulation with a 0.30 m channel separation and SD_{2ply} is the standard deviation of flat section thickness under a silicone bag for a 2-ply layup. Equation 36 was used to calculate a value of $d = 1.0$ mm. The dimensions of the cavity to be machined in the foam core to fit the servo mounting bracket based on an assumed skin thickness of 1.0 mm are shown in Appendix H.

6.3 Results of infusion optimization

The techniques developed in Chapters 4 and 5 were used to optimize the manufacturing of the GeoSurv II mission avionics hatch and empennage. A fast and inexpensive

infusion method that results in few corner voids was required for the main hatch, so the Stretchlon bagging technique was used. The hatch infusion was simulated, and the results of the simulation were used to modify inlet placement to achieve complete infiltration of the preform with resin.

The empennage, on the other hand, required a technique that could achieve a higher level of compaction, and faster resin flow to minimize final part weight and guarantee a successful infusion. To that end, the silicone manufacturing method was selected to infuse the empennage. The mould emptying simulation developed in Chapter 4 was used to select an optimum flow channel separation, and predict final part dimensions.

To complete the manufacturing of the empennage, the foam core that has been manufactured by the 2012/13 Structures team must be wrapped in carbon fibre and peel ply. A custom bag must then be manufactured around the preform and core and the empennage must be infused with resin. This process is scheduled to take place in summer 2013.

The optimization procedures developed in Chapters 4 and 5 proved to be effective tools for tailoring the processing parameters of VARTM infusions to meet a range of final part requirements.

Chapter 7

Conclusions

This chapter outlines several important conclusions that were made from this research, and discusses recommendations for future work.

7.1 Conclusions

- A mould filling simulation was developed that incorporates the effects of the flexible bag used in VARTM processes. A novel permeability estimation algorithm was developed and used to characterize the permeability of woven carbon fibre fabric. It was found that interactions between the vacuum bag and the preform could significantly alter preform permeability.
- The resin emptying behaviour of parts made using the VARTM process was modelled, and this simulation was used to select an infusion scheme that achieves maximum compaction of the laminate, and reduces thickness variations. It was found that the amount of resin that can be removed from the part during resin emptying can have a significant effect on thickness variation. For example, when the resin emptying behaviour of a two-ply layup of BGF 94107 woven carbon fibre cloth was simulated, it was found that a 0.254 m long specimen contained a maximum thickness variation of 36.1%, but this could be reduced

to only 12.1% if the distance between inlet and outlet is decreased to 0.203 m. The resin emptying behaviour of the preform can be improved by increasing preform permeability.

- The presence of an inside corner can cause local decreases in the compaction pressure applied to the preform. This loss of compaction pressure can lead to void accumulation and thickness variation in part corners.
- Corner radius is a significant factor when determining thickness variations, void content, and strength of "L"-channel test specimens. Increasing the radius of the corner had a positive effect on these three parameters, with the most significant increase in performance occurring in specimens with a corner radius between 6.4 mm and 12.7 mm.
- Parts containing an outside corner were observed to contain a 3% thickness increase when compared to flat panel values, whereas parts with an inside corner contained an 18% average thickness increase. Inside corners performed worse in void accumulation as well; corner voids were found in 17% of parts containing an outside corner, compared to 54% found in parts containing an inside corner. Higher average failure load and curved beam strength were observed in parts containing an inside corner, which was attributed to the thickness increase in the vicinity of the inside corners. However, the variability in strength was also significantly greater in parts containing an outside corner.
- The presence of a void was not found to significantly affect the average failure strength or curved beam strength of the test specimens. However, the presence of a corner void did increase the standard deviation observed in specimen failure strength and curved beam strength by 37.3% and 35.9%, respectively. It was found that interlaminar strength calculations cannot accurately be applied when

parts have a low tolerance on thickness and radius.

- The CCBM method developed by Mahendran will, in general, produce stronger parts with less thickness variation when compared to parts made using the Stretchlon bagging method. However, the integrity of the seal that is achievable using the CCBM method is less than when a thin film bag is used, and this leads to more significant corner void formation in CCBM parts. Furthermore, the CCBM method requires much more preparation time. For that reason, parts that need to be made quickly, without corner voids should be made using the Stretchlon bagging technique with pressure enhancers.
- The mission avionics hatch required a smooth surface finish with minimal voids, and a manufacturing process that not expensive or labour-intensive. For that reason, a VARTM infusion was used with a female mould, Stretchlon vacuum bag and silicone pressure enhancers. The infusion of the hatch was simulated, and it was found that spiral flow tubing around the edge of the mould was required to fully infuse the part. The hatch was infused using the method developed through simulation, and the infusion flow front followed the predicted path until the flow front reached resin outlets. After the resin reached the outlets, the flow front motion predicted by the simulation deviated from the actual motion due to inaccuracies in the modelling of resin outlets.
- The inverted V-empennage that will be manufactured for the GeoSurv II UAV is required to be as light as possible, with high strength, so the CCBM process was selected to manufacture the empennage. The resin emptying simulation was used to determine that a resin distribution channel spacing of no greater than 0.30 m will minimize thickness variations within the empennage. The servo mounting plate cavities in the empennage were sized based on the studies conducted on thickness variation and resin emptying simulations, and it was

found that a thickness increase of 1.0 mm will provide sufficient clearance for the servo mounting plates.

7.2 Recommendations

- During the course of this research, it was observed that the PT2712 resin would experience significant off-gassing of volatiles when vacuum pressures below 50 kPa were drawn, which led to micro-voids forming between the tows of the fabric. Other resins should be investigated, and a resin should be used for future manufacturing that will not release volatiles under vacuum pressure. Applied Poleramic Inc. makes a toughened two-phase epoxy called SC-15 [71] which could be an effective alternative to the PT2712 resin that was used for this research.
- Significant improvements in composite part quality could be achieved through the use of resins that require an elevated temperature to cure. This would permit the infusion to be conducted at room temperature without the use of distribution medium, and sufficient pot life would remain after infusion to fully remove excess resin, producing parts with minimal thickness variations and a smooth surface finish. Then, the mould and preform could be heated to cure the resin. A resin should be found that has a long pot life at room temperature, but will cure at temperatures no higher than 50°C to minimize deformations due to thermal expansion of the mould, and permit low temperature vacuum bagging supplies to be used. One resin system which meets these requirements is the Prime 20LV resin made by AMT Composites [72]. The Prime 20LV resin system has a working time of 10 hours at room temperature, but this can be reduced to 6 hours at 30 °C.

- It is undesirable to use nylon mesh distribution medium on parts made using the Mouldless VARTM process, as the mesh frequently leaves an imprint on the surface of the part. This limits the use of the Stretchlon bagging technique for Mouldless VARTM manufacturing, as the reduced permeability associated with the highly flexible bag tends to result in incomplete infusion. Alternative methods of enhancing flow rate when using Stretchlon bag should be investigated. One promising technique is replacing the nylon mesh distribution medium with a layer of polyester bleeder/breather ply. This layer has been found to enhance flow rate, and has the added benefit of giving volatiles a path out of the preform. One promising product is AirTech's Breatherflow 60, which is designed to act as a breather cloth and distribution medium for VARTM processes, and will not collapse under pressure [73].
- The inlets and outlets, and linear flow channels were found to locally disturb the preform when placed directly on the surface. Methods for placing inlets, outlets, and linear flow channels that do not disrupt the surface finish if used with a non-reusable bag should be developed.

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Appendix A

LIMS simulation mesh convergence

Figure 86 shows the simulated position that a flow front position reaches at cure plotted against element size.

Figure 86: Effect of number of element size on flow front cure position

Appendix B

3-view diagram of corner test part mould*

Figure 87: 3-view diagram of corner test part mould

*All dimensions in mm.

Appendix C

Four point bend apparatus

Appendix D

Material properties used to determine laminate stiffness

Table 9: Properties of carbon fibre lamina made using BGF 94107 woven fabric and PT2712 epoxy resin

Resin stiffness (fully cured)	3.4 GPa [53]
Fibre stiffness	230 GPa [74]
Carbon density	1760 kg/m ³ [74]
Fibre area weight	0.37 kg/m ² [75]
Poisson's ratio (fibre)	0.2 [76]
Poisson's ration (matrix)	0.4 [77]

Appendix E

Procedure used to manufacture MDF hatch mould

The following procedure was used to manufacture the MDF mission avionics hatch mould [78]:

1. Sheets of $4' \times 8' \times 0.75''$ MDF were cut to the size of the mission avionics hatch and were laminated together to build up the mould to the desired thickness. A two-part West Systems epoxy was used to laminate the MDF sheets. A layer of epoxy was placed on both mating sides, and weights were used to hold the MDF sheets in place.
2. The mould was machined using a CNC router table.
3. After machining, the mould surface was rough, and contained numerous ridges left by the tool paths. The surface was sanded with 180 grit sandpaper to remove these ridges.
4. Grooves were left in the mould at the interface between the MDF layers. These grooves were filled with Bondo filler, and sanded smooth.
5. Three layers of TechnoSeal 2106 from Polymeres Technology were used to seal

the mould. Each layer was applied as thin as possible with a cloth, and allowed to cure. Sealing the mould is an important step in mould manufacturing because it prevents resin from infiltrating the MDF during infusion, which interferes with de-moulding of the part and leads to mould damage.

6. The mould was polished to achieve a smooth, high-gloss surface finish. A sanding block was used with increasingly fine grades of sandpaper. Initially, 180 grit sandpaper was used to smooth the surface of the mould. 400, 600, 800, and 2000 grit sandpaper was then used sequentially to achieve a high-gloss finish. This step is extremely important, and the amount of care and effort taken to polish the mould will determine the surface finish quality of the parts produced using the mould.
7. Three layers of mould release wax were applied to the mould surface to prevent the part from bonding to the mould. At least 30 minutes were allowed between each layer to allow for the wax to harden. Care was taken to avoid putting wax around the edges of the mould, as this was found to interfere with the seal between the tape and the mould, and can lead to leaks during infusion. After the final layer of wax was applied, the excess wax was removed by gently wiping the mould with a cloth.

Appendix F

3-view diagram of mission avionics hatch mould*

Figure 88: 3-view diagram of mission avionics hatch mould

*All dimensions in mm.

Appendix G

3-View drawing of servo mounting bracket

The relevant dimensions of the servo mounting bracket are shown in Figure 89.

Figure 89: Servo mounting bracket

Appendix H

Servo mounting plate cutout size

The dimensions of the opening to be cut in the empennage foam core to accommodate the servo mounting plate are shown in Figure 90.

Figure 90: Opening size required to accommodate servo mounting plate