Development of Vacuum Assisted Composites Manufacturing Technology for Wind Turbine Blade Manufacture

by

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Declaration

I declare that no material contained in the thesis has been used in any other submission for an academic award and is solely my own work

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School ______________________________

Dedication

To my loving wife Paula for her care, understanding and support whether deserved or not. To my wonderful children Laura and Christian who make me so proud for their patience and understanding when other things seemed to take priority. Also to my colleagues for their consideration and guidance and to Paul Hibbard, a fine engineer, for his advice and guidance

With special thanks to Prof. Xiongwei Liu and Dr Justin Whitty for their help and support throughout.

Abstract

Wind turbine blade manufacturers employ the vacuum infusion technique to produce monolithic and sandwich cored components, recent innovations have seen companies such as Siemens develop products which incorporate an internal composite structure in a single process (Siemens 2008). This thesis explores the technique of resin infusion and develops a manufacturing process to allow a small wind turbine blade to be manufactured in a single process complete with its internal structure.

An innovative manufacturing method for creating three-dimensional internal structures within composite components is presented. A technique is developed for the production of polymer matrix composite products containing both external faces and internal structures in a single process. The main focus is on the production of small prototype wind turbine blades although the technique is transferrable to other hollow or foam cored composite products.

This work leads to the manufacture of prototype 2.5m fibreglass wind turbine blades and their internal structures in a single process. The technique developed forms the structural spar section as an integral part of the wind turbine blade. Methods of infusing resin within a closed mould environment are developed utilising custom resin channels to control the nature and rate of resin infusion through the structure.

Investigation of a range of core materials used in composites manufacture to improve stiffness, strength and fatigue was explored. A range of specific reinforcement materials and resin systems are tested to determine a suitable laminate structure for blades that complements the vacuum assisted method.

Methods for the manufacturing and fabrication of blade plugs and composite mould tooling are presented with features to facilitate the use of the vacuum assisted manufacturing technique. Equipment and execution of the process is given.

Findings are applied to produce a composite component with internal structure comparable to current manufacturing methods targeted around small wind turbine blade manufacture.

Results conclude that the development of a process to manufacture a complete wind turbine blade in a single process is achievable and feasible. Results and outcomes of the research are presented with recommendations and suggestions for future work.

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Chapter 1 Introduction

Resin infusion (RI) is a common technique in the manufacture of wind turbine blades, there are many patented variations on the process (VARTM, SCRIMP, VIP, CVI etc.) but most processes typically involve resin being drawn through a laminate under vacuum or assisted by pressure. The process is often misunderstood and considered unpredictable and problematic (Hanson 2009). A trial and error approach to establish a consistent and repeatable process is often the case until the process is fully understood.

1.1 Background

Vacuum assisted manufacturing methods are commonly used with monolithic or single skinned components or components with flat sandwich core material. Wind turbine manufacturers Seimens have successfully developed what has been named a 'one shot' process (Siemens 2008) creating a large wind turbine blade in a single process incorporating both the skins of the blades and the internal three-dimensional structures such as spars and beam sections within the component. This process is somewhat secretive.

New materials are being developed with three dimensional weaves and woven-in reinforcing structures (Tong 2002) but do not address particular internal structures within a component.

1.2 Aims and objectives

The research aims to develop innovative manufacturing technology to allow the manufacture of a wind turbine blade which incorporates internal structures as well as the outer skins of the blade in a single process. This technology would also be transferable to any hollow composite product with internal structural members.

This has involved initial research into current materials and manufacturing processes and in particular vacuum assisted resin infusion methods with the aim of developing them to allow the manufacture of internal spars and supporting structures as an integral part of the turbine blade.

Work described defines the nature of resin infusion across varying sections of both reinforcement material and sandwich core structures to determine a consistent and repeatable process.

1.3 Objectives:

The objectives of the project are:

- to develop innovative manufacturing methods for creating three-dimensional internal structures within composite components in one process
- to investigate and incorporate the use of vacuum assisted resin transfer techniques in the manufacture of internal structures
- to investigate and utilise a range of core materials used in composites manufacture to improve stiffness, strength and fatigue in composite components
- produce a composite component with internal structure comparable to current manufacturing methods targeted around small wind turbine blade manufacture

1.4 History

Historically composite materials have been a common material selection for wind turbine manufacture (Povl Brøndsted August 2005). Such materials satisfy the operational requirements for wind turbine blades namely:

- High stiffness to maintain the aerodynamic shape of the blade during operation
- Low density to reduce the gravitational forces acting on the blade
- Good fatigue resisting properties to withstand the cycling

Initially wet lay-up techniques were replaced by vacuum assisted techniques which, although developed in the late 1950's were not employed until the 1990's in wind turbine manufacture. (Povl Brøndsted August 2005)

With three bladed turbines being the norm, the consistency of each blade must be closely controlled. The use of vacuum assisted techniques led to better process control and therefore improved quality and repeatability.

Development of pre-impregnated reinforcements (pre-preg) has also become a technique often used within the industry giving the same repeatability and consistency required.

Thermoplastic reinforced fibres (PEEK/PP) have been developed and tried but for use in the wind turbine industry the process is hindered by the high processing temperatures (250-390^{o}C) and difficulty in achieving suitable secondary adhesive bonding. (van Rijswijk 2007)

In summary with polymer matrix composites continuing to be the materials of choice within the industry, there is still room for the development on new and improved techniques and materials in this sector. The following chapter highlights pertinent literature on the subject.

Chapter 2 Literature review

Composite manufacturers continue to try and improve the strength and quality of components whilst also seeking to improve the manufacturing process and reduce environmental impact. This leads to three definitive areas for research (i) composite materials (ii) structure of composites and (iii) manufacturing processes. This chapter will focus mainly on the structure of components and the manufacturing processes and particularly vacuum assisted techniques; however direction also focuses upon materials currently available for manufacture. Attention is given to the manufacture of small wind turbine blade and the creation of internal structures.

2.1 Manufacturing technology of composite products

There are two main processes used in wind turbine blade manufacture: (a) vacuum assisted resin transfer techniques and (b) pre-impregnated materials (pre-preg). This research has not focused on manual wet lay-up or methods used with pre-preg materials including automated CNC tape laying which is being adapted to wind turbine blade manufacture (Stewart 2009).

There are numerous technologies which make use of vacuum to assist in producing a composite component i.e Vacuum Infusion Process (VIP), Controlled Vacuum Infusion (CVI), Vacuum Assisted Resin Transfer Molding VARTM, Resin Infusion(RI), Seeman Composites Resin Infusion Molding Process (SCRIMP). Such processes provide consistent laminates and all follow a similar principle of introducing the polymer matrix resin into the reinforcement under vacuum or pressure. These processes aim to give consistent fibre to resin ratio as well as providing good consolidation of the composite materials to the mould surface whilst avoiding voids within the laminate (Hanson 2009).

Vacuum Infusion allows large components to be infused in a single process giving consistent consolidation of reinforcement and matrix under vacuum giving consistent and repeatable results. Reinforcement materials are laid dry into the mould along with infusion media which assists the flow of resin through the laminate. The mould is sealed within a vacuum removing air from the laminate and consolidating fibres to the mould surface, resin is then introduced and flows through the infusion media then down into the reinforcement materials. (Berry 2007)

Successful resin infusion is often achieved through trial and error backed up with test samples produced to determine rates of infusion rather than specific guidelines or theory. Active control of RI has been developed with solenoids controlling valves whilst the laminate is monitored for infusion through the laminate (Modi 2007). Software such as PolyWorx ®exists to simulate the infusion of a component and is often used as a starting point for a new component or refining a process to reduce resin waste or rectify problematic areas. (A. Koorevaar 2002)

An alternative to VI is Resin Transfer moulding (RTM) differs from vacuum infusion in that the resin matrix is injected into the reinforcement material under pressure, often assisted by vacuum. This often requires a male and female mould and tooling to resist injection pressures.

2.2 Manufacturing methods

With very few exceptions wind turbine blades are manufactured by laminating the top and bottom skins of the blade separately, a central stiffening spar is also manufactured separately and bonded to the blade skins (Gobson 2006). The company Siemens have developed a 'one shot' process where the internal structures and skins are processed in one single operation meaning no bonded joints or separate parts. This design process is highly secretive within the industry however this research indents to replicate a similar outcome for the production of smaller scale wind turbine blades.

A typical wind turbine blade skin is produced in a female mould with top and bottom skins being manufactured in separate moulds often hinged together so top and bottom skins can align correctly at the bonding stage. The skins are commonly fabricated from multi axis reinforcement materials with a foam core either side of a central spar cap, the whole skin is infused in one single operation. (Jensen June 2003)

Structural spars inside a wind turbine blade are typically a sectional profile typically Box-section, I-section or C-section; which are either moulded around a shaped mandrel or within a mould separate from the blade skins themselves but are commonly manufactured with spars which are in the form of a foam core shear plane with uni-directional fibres incorporated in the top and bottom region of the spar and biaxial fibres along the length.

Methods have been discovered which allow internal structured to be created within a hollow composite parts. Within the motorsport industry aerodynamic wing sections are commonly manufactured using pre-preg methods with internal spars and silicone cores which hold the spars in place (Freeman 1987). This can also be achieved by using inflatable bladders, that, when inflated, expand to the shape of internal spars or webs containing them. After curing of the part the silicone cores or bladders are removed. Another process is to laminate around dissolvable cores which can be removed once curing is complete (Ender 2009). It is considered some adaptation of these methods combined with vacuum infusion techniques will provide a solution for this research.

Blade skins, central spar and sometimes a root section of the blade are commonly adhesive bonded together, Epoxy adhesive pastes are common, cured at an elevated temperature, leading edges and trailing edges of the blade are often hand finished and filled as overlapping of the skins to give a wide bondable area are required (Hibbard 2010). Fatigue failures have been attributed to delamination of bonded components (F.M. Jensen 2006) therefore the development of a process to eliminate secondary bonding of the spar section to the skins of the blade may eliminate or reduce the likelihood of failure.

2.3 Reinforcement materials

Fibreglass remains a dominant reinforcement material within the wind turbine industry. Carbon Fibre is also used. Some blades are manufactured almost entirely from Carbon Fibre, other manufacturers use the more exotic material in highly stressed areas such as the spar cap region. The nature of the reinforcement material is primarily as a structural element of the blade but must also complement the manufacturing process. The vast majority of wind turbine blades are manufactured using Fibre reinforced polymer matrix composites or Fibre Reinforced Plasics (FRP) with a range of fibre reinforcements predominantly fibreglass and carbon fibre held together with a polymer matrix typically Epoxy, Polyester or Vinylester. Some blade manufacturers are now moving towards Pre-Impregnated materials (Pre-preg) (Ashwill 2007) commonly used in high end aerospace and motorsport applications which have the resin already impregnated into the reinforcement material. Both fibreglass and carbon fibre reinforcements are used and often used in combination, fibreglass is a less expensive material approximately a tenth of carbon fibre but does not possess the tensile strength and stiffness of carbon which is up to four times stronger than its fibreglass counterpart (Gobson 2006) Cost benefit and material availability are often factors that determine their use.

2.3.1 Reinforcement

Both fibreglass and carbon fibre reinforcement materials can be produced in a range of textile forms for use in composite manufacture; within the wind turbine blade industry several forms of reinforcement materials are commonly used. These are typically Uni-Directional UD), Bi-Axial (BIAX) and Tri-Axial cloths (TRIAX).

Uni-Directional (UD) materials consist of long strands of continuous fibre either as single rovings or loosely stitched into a cloth. With fibres having strength in one direction this allows for reinforcement to be placed onto a component to best resist the direction of forces. UD fibres are also commonly used on the top of structural spars along the length of a turbine blade to prevent flex under flapwise loading. Similarly along the leading and trailing edges to counteract flex in edgewise loadings

Bi-Axial reinforcements are unidirectional strands positioned in layers at $+45^{o}$ and -45^{o} degrees to each other. The fibres are stitched together into a cloth. This gives fibre strength in two directions and is commonly used on the outer skins of wind turbine blades where torsional strength is required to resist twisting along the length of the blade, it is also used down the length of central spar sections which are subject to bending. These types of material wet out with resin easily as the fibres are not twisted or randomly arranged as in other textiles.

Tri-Axial and Quadrilaxial materials contain unidirectional fibres stitched together with varying quantities in different axes, for Tri-Axial the fibres are typically 50% of fibres at 90^{o} and 25% each at $+45^{o}$ and -45^{o} Typically used for outer skins but provides most strength along its length and can be used instead of providing a dedicated unidirectional spar cap.

Woven roving fibreglass and carbon fibre dominate within the composites industry but are scarcely found in wind turbine manufacture except for pre-impregnated materials. The range of woven reinforcement materials (i.e. plain, twill, satin weave) by their very nature, contain fibres that pass over and under each other and therefore rovings are not as linear as axial reinforcements therefore do not transfer loading in the direction of the fibres as effectively. With pre-impregnated materials woven fabrics are preferred due to the manufacturing process of impregnation itself, multi axial pre-preg materials are possible but not common.

2.4 Polymer matrix materials

The role of the matrix i.e. resin, is to support the reinforcement material and distribute loads through it. Three polymer matrix materials are commonly used in wind turbine blade manufacture, namely Epoxy, Vinylester and Polyester resins.

Epoxy resins are the most expensive but have properties which are often superior other resins such as Polyester and Vinylester (Al 1999). Resins have been developed specifically for resin infusion and offer low viscosities and low exothermic reaction allowing thick laminates to be infused at room temperature with elevated temperatures required to cure the resin.

Vinylester Resin is common in both wind turbine blade and marine applications, Vinylesters provide excellent properties often comparable with Epoxy but are more cost effective. Vinylesters have also been developed specifically for resin infusion offering low viscosity and low exothermic reaction

Polyester Resin is the least expensive and most widely used within the composites industry. Polyester resins are not typically used in wind turbine blade manufacture, although some Polyesters can exhibit reasonable properties, they are considered inferior to Epoxy and Vinylester resins.

2.5 Core materials

Sandwiched core materials have long been associated with composites manufacture to enable the creation of stiffened structures with excellent strength to weight ratios (P Myler 2003).

It is common to produce sandwich core laminates using vacuum assisted techniques and there are core materials and foams specifically developed for infusion. Core materials used in wind turbine blade manufacture vary but typically closed cell foams and balsa are used.

Closed-cell foam materials such as such as PVC Acrylic, Polyurethane and more recently PET have been developed in sheet form with holes and/or irrigation channels to assist resin flow under vacuum. These core materials are widely used in both wind turbine and aerospace applications.

Although a natural product the consistent density of balsa and its compressive strength still make it a viable and widely used material for wind turbine blade manufacture, some foams are now superseding its properties and are being used in favour of balsa. Leading manufacturers Seimens and Vestas have both used balsa in the manufacture of their large blades. (Hibbard 2010)

Honeycomb materials such as Nomex do not lend themselves to the vacuum infusion process as liquid resin would enter the cells of the foam during infusion. However, honeycomb cores may be found in blades manufactured using pre-preg materials as the process does not use resin in liquid form and can utilise resin films to adhere reinforcement materials to the honeycomb without resin falling into its cell structure

2.6 Simulation software

The use of software to simulate the flow of resin through RTM or vacuum assisted techniques is available, leading software RTM Worx by Poly Worx developed by Arjen Koorevaar uses a generalised version of Darcy's Law and Continuity Equation to develop a model for flow through porous media with generalised Newtonian fluid theory using Navier Stokes equations to determine flow through sections with no reinforcement materials. The software allows the user to insert inlet and outlet ports to determine the optimum layout for achieving a full infusion. Examples of the software and its successful use in industry is evident. (A. Koorevaar 2002) For this research such software was unaffordable and from consideration of examples shown the software did not appear to have the capacity to vary rates of flow through channels and that an overall permeability values for a laminate was required which would be difficult to predict without practical investigation. Such parameters are critical to effective design. Ansys® CFX and Abacus® can also verify RI processes.

2.7 Closure

The literature review has concentrated on investigations into the structure, manufacturing techniques and materials used in the production of hollow composite parts including Wind Turbine blades. Its aim was to identify current materials and manufacturing technology and highlight areas of development which will allow the manufacture of a composite part that incorporates all internal structures as well as the outer skins of the component in a single process.

The review has initially discovered which composite reinforcement materials and resins are most commonly used and in which forms the fibre reinforcement takes. The orientation of fibres to best withstand the distribution of forces through composite blades has also been investigated.

The use of sandwiched core materials for improved stiffness has been explored and types of core materials used within the industry have been investigated as well as materials specifically developed to suit the manufacturing processes involved in blade manufacture, combining cores with reinforcement materials has been identified as a key area for research and development.

To fulfil the aim of developing an innovative manufacturing method, common manufacturing techniques have been investigated and in particular the use of vacuum infusion methods which would lend themselves to the creation of internal structures in a single process. The nature of the process and its limitations has been considered to establish how it may be utilised to create internal structures within a hollow composite component.

With one of the principle aims of the research being to eliminate the bonding process completely, this survey also considers current methods of bonding and assembly of blades which can sometimes act as a weakness to the blade structure particularly its fatigue strength. Fatigue failure in composites appears more complex than it is in metals with straight fibres and environmentally resistant resins major contributors as well as the designed structure of the component. (John F. Mandell 2002)

Processes outside of wind turbine manufacture which already incorporate internal structures have been considered, This includes the use of removable silicone cores and inflatable bladders to support internal features during component curing, once cores/bladders are removed, the internal structures remain intact. This is seen as key to the research as similar methods of supporting structures married with the vacuum infusion process should form the basis of a new innovative process.

The predictability of resin flow lends itself to numerical solutions to predict flow through a porous media and that software exists to simulate infusion time and display the nature of flow through porous media.

The conclusion of the literature review is that a viable and innovative solution is feasible and could lead to the development of an internal structure within hollow composite parts such as wind turbine blades using vacuum assisted composites techniques.

Chapter 3 Initial benchmarking experiments

Extensive trials with the VI process were conducted in order to observe and record findings to better understand the process and its capabilities. These trials practiced and developed the process to give consistent and repeatable outcomes and explored a range of materials available to gain best results.

3.1 Initial trials

Initial trials were conducted on flat surface moulds for ease of execution and observational purposes. Following on from this two wind turbine blade moulds were manufactured to facilitate this experimental process. A 1m mould was taken from an existing blade and a 2.5m mould manufactured from a 3D CAD model as shown in Figure 3.1

Initial trials served to benchmark the process via initial prediction of the behaviour of resin flow through a component using the VI method. Further trials using specific resins and reinforcement materials and resins specific to the process were undertaken. This led to full infusions of blade sections and complete blade profiles.

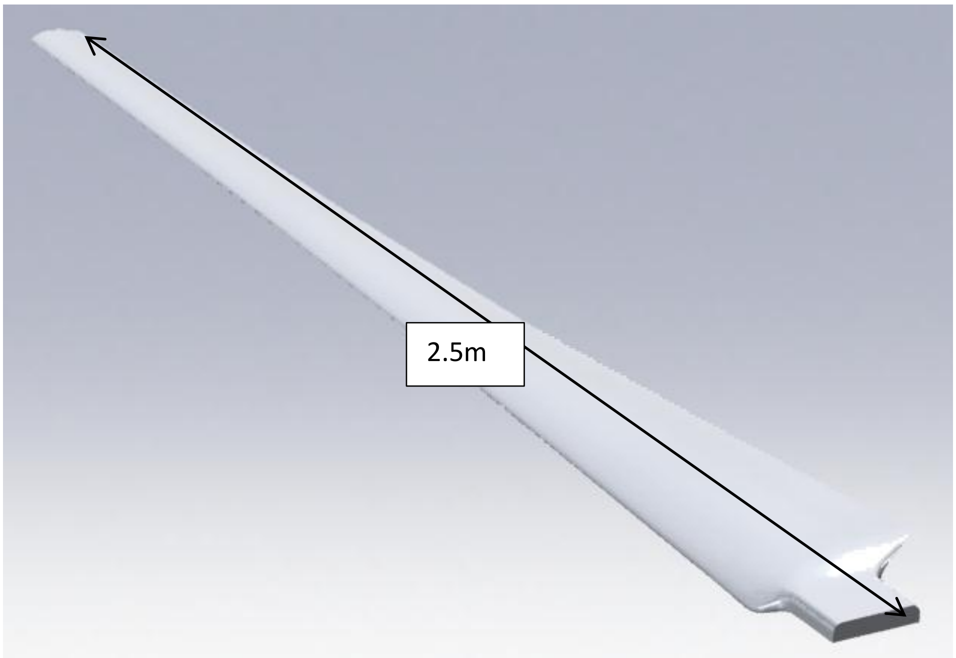

Figure 3.1 CAD model

3.2 Vacuum infusion method

Resin Infusion differs from conventional wet lay-up techniques in that that the reinforcement i.e. fibreglass, is laid into a mould dry; rather than pre-wetting or saturating the fibres. A porous release film or peel-ply is laid over the reinforcement then an infusion mesh is laid over that. The whole laminate is then sealed under vacuum beneath a vacuum bag which is sealed at the mould edge with a sealing tape. Resin inlet and vacuum outlet ports are created to facilitate resin entry, the placement of which vary; this set-up is used within this work and shown in Figure 3.2

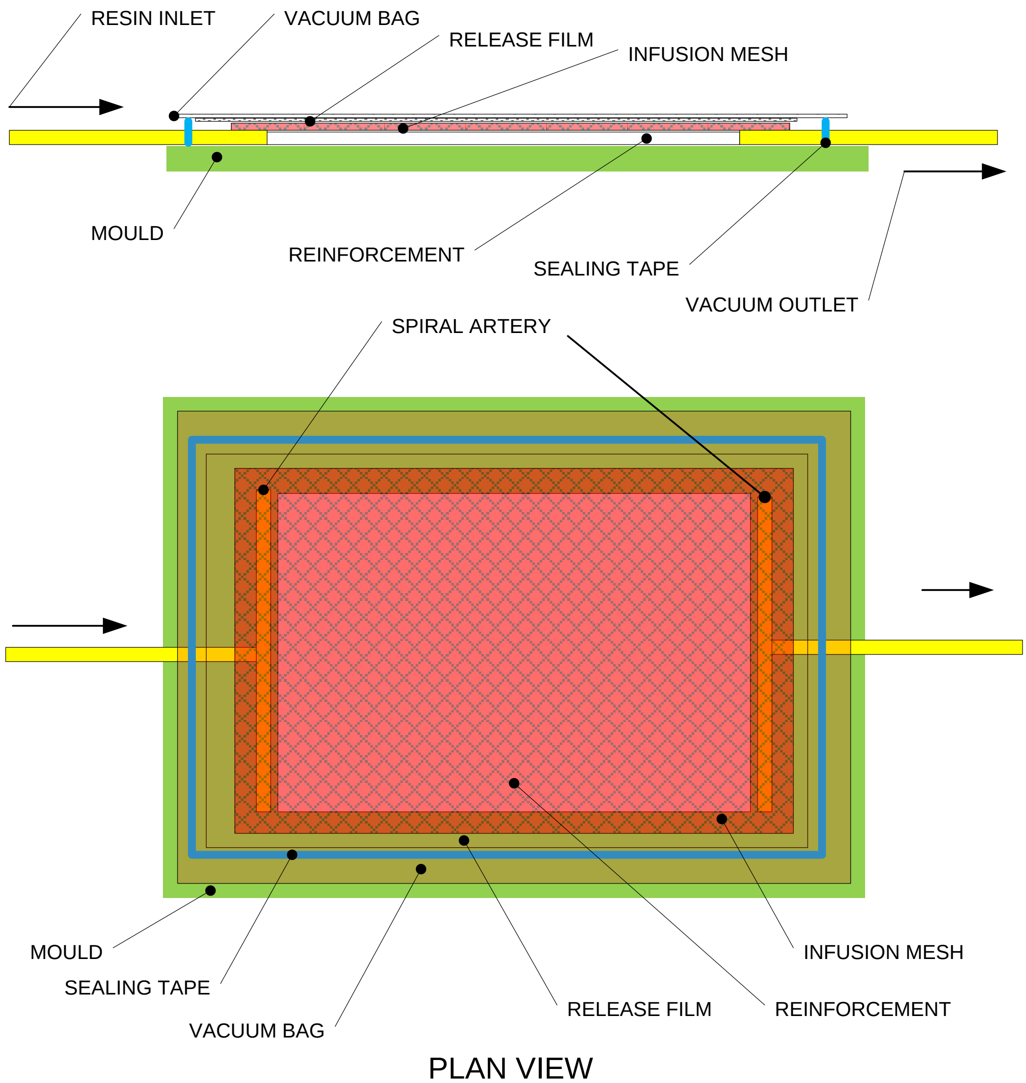

Figure 3.2 Orthographic projection of VI set-up

Resin was released into the mould under vacuum. A spiral binding artery under the infusion mesh served as a channel for resin to rapidly flow across the width of the reinforcement. The pressure differential between the vacuum outlet and resin inlet (open to atmosphere) encouraged the resin to flow across the infusion mesh and down through the porous release film into the fibreglass reinforcement. Once the mould was fully infused the resin inlet was shut off and vacuum maintained until resin reached the gel stage following which a partial vacuum was applied until the component had cured.

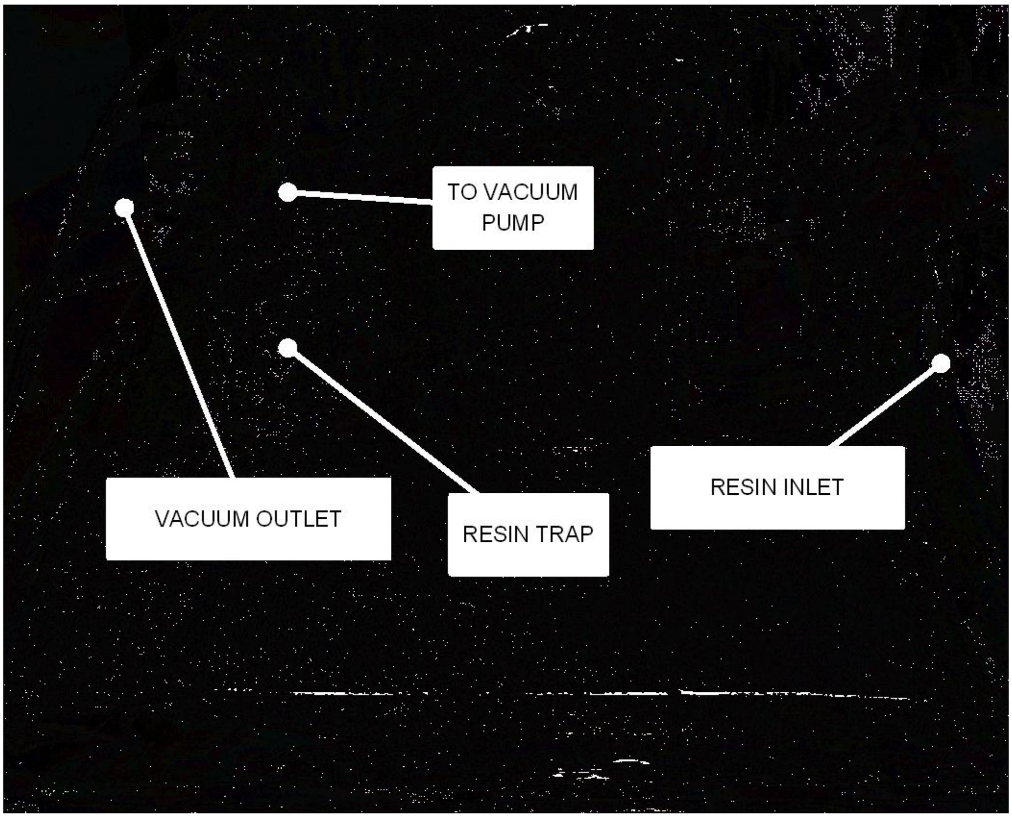

Figure 3.3 Vacuum infusion set-up

Excess resin was collected in a resin trap, resin reached some regions of the laminate before others, often several vacuum lines were installed and closed once infusion was complete, the trap served to collect excess resin without resin passing through to the vacuum pump as shown in Figure 3.3

The mould surface for initial trials was a sheet of safety glass, this gave a polished surface finish and allowed the flow front at the mould surface to be observed and recorded. Further trials were able to be conducted with the vacuum bag forming the mould surface again allowing observation at the mould surface.

The volume fraction a comparative test was established by weighing 50mm diameter discs cut at regular intervals along the cured laminate as shown in Figure 3.4. With known densities for both resin and fibre, volume fraction was determined using Equations (3.1) and(3.2)

Standard testing procedures for volume fraction are documented (ASTM D3171 – 09) where detailed analysis can be obtained by resin burn off which can also determine the quantity of volatiles trapped within the resin. This however was not considered practicable due to specialist equipment needed.

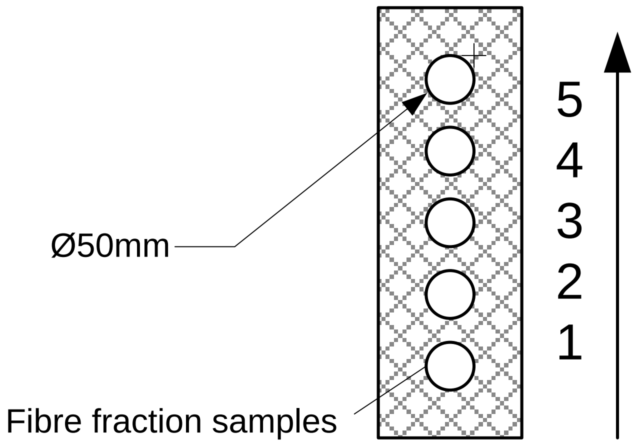

Figure 3.4 volume fraction samples

Fibre Volume Fraction (V_f)

$$\frac{1}{\rho c} = \left(\frac{Wf}{\rho f} + \frac{Wm}{\rho m}\right) \tag{3.1}$$

$$Vf = Wf\left(\frac{\rho c}{\rho f}\right) \tag{3.2}$$

where:

V_f is the volume fraction (fibre),

ρc is the density of composite (g/cm^3)

ρf is the density of fibre (g/cm^3),

ρm is the density of resin/matrix (g/cm^3),

Wf is the weight fraction (fibre) and Wm is the weight fraction (matrix)

Initial Vacuum Infusion trials were carried out using standard reinforcement materials primarily Chopped Strand Matt (CSM) and Woven Roving Fibreglass with general purpose Polyester and Vinylester laminating resins.

A range of Aerovac infusion media were tested to observe and record the rate of resin infusion and the manner in which it flowed through the reinforcement. The number of laminate layers was also tested to determine what thickness of laminate could be successfully infused in a single process.

These tests gave the opportunity to compare the flow front across a range of infusion media with the flow front along the mould surface.

3.3 Infusion media trails

The Infusion Meshes sampled differed in their flexibility and mesh density. Under vacuum it was predicted the stiffer and coarser mesh densities would infuse at a faster rate. Compaction of the mesh under vacuum would still leave cavities for resin to flow but stiffer and coarser meshes would have more cavities therefore allowing resin to flow better.

Past experience showed the rate of infusion slowing towards the end of the infusion. This should be attributed to the pressure differential between inlet and outlet decreasing, hence affecting the velocity Full vacuum was only be re-established once the resin inlet was shut off.

Investigation of consumable materials available to the industry showed a variety of products suitable for RI. Selection of a range of consumables allowed comparison between them and determined the effectiveness and nature of resin flow through a laminate using a range of infusion meshes and release films. The following materials were used in the initial trials.

3.3.1 Infusion Media

With the role of infusion media being a conduit for resin flow under vacuum, a range of materials were tested as listed in Table 3.1 the density and stiffness were found to affect the nature of flow through them.

Product	Ref	Material	Colour	Weight
Infusion Mesh	Vi1	Polyethylene	Blue	200 g/m^2
Infusion Mesh	Vi2	HDPE - Hard	Green	230 g/m^2
Infusion Mesh	Vi2s	HDPE - Soft	Green	200 g/m^2
Infusion Mesh	Vi5	PET	Translucent	200 g/m^2

Table 3.1 Infusion Media

3.3.2 Release Materials

Perforated release film and peel ply were selected for use, as resin would have to pass through them into the laminate it was deemed necessary to measure the performance of each. Each is listed below in Table 3.2

Product	Ref	Material	Colour	Weight
Release Film	A2200	PE	Opaque Orange	80 g/m^2
Peel Ply	A8888	Nylon	White / red stripe	80 g/m^2
Peel Ply	B4444	Nylon	Green	80 g/m^2

Table 3.2 Release Film / Peel-Ply Materials

3.3.3 Reinforcement materials

Initial tests were conducted on reinforcement materials commonly available of different densities to determine the effectiveness of the infusion upon them. The following types and weights of material were tested as listed in Table 3.3

Material	Weight (g/m^2)	Density (g/cm^3)
CSM Fibreglass	300	2.56
CSM Fibreglass	450	2.56
Woven Roving Fibreglass	300	2.56
Woven Roving Fibreglass	600	2.56

Table 3.3 Reinforcement Materials

3.3.4 Polymer matrix materials (resins)

Two resins were selected for infusion as listed in Table 3.4; although not specifically developed for RI each would serve adequately to establish the process method.

Resin Type	Reference	Density
Polyester	Cray Valley Encore 30	1.4 g/cm^3
Vinylester	DOIN 9100-700	1.3 g/cm^3

Table 3.4 Resins

3.4 Initial observations

To compare infusion media materials, several samples were prepared on a single flat mould surface with different types of flow media across a common reinforcement laminate and release film. Figure 3.5 shows resin being infused from the resin inlet towards the vacuum outlet as shown in Figure 3.6. Lines drawn across the sample indicate the rate of infusion across the mould in 10 second intervals.

Figure 3.5 Infusion benchmarking tests

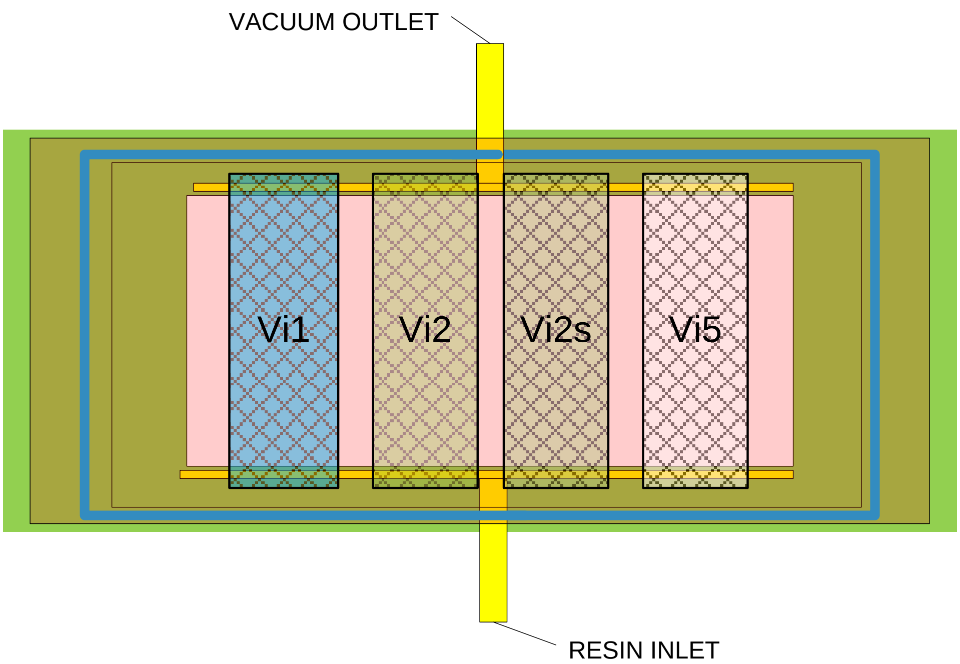

Figure 3.6 Infusion Inlet / outlet positions

In order to determine the effectiveness of the process with regard to multiple reinforcement plies, tests were conducted to observe and record the nature of resin flow through multiple reinforcement layers. Observation of lag was also recorded to determine if laminate thickness was a factor influencing the rate of resin flow at the mould surface compared to the infusion media surface..

Trials were conducted to observe and record the infusion of multiple laminates of reinforcement. Laminates consisting of 3 to13 plies of 450g/m^2 CSM were prepared on a mould and infused in a single infusion, the experiment was arranged as shown in Fig 3.6 so that each sample was infused under the same conditions.

Observations were made at the flow front and mould front surfaces through the flat safety glass plate mould.

3.4.1 Infusion Media Trial Laminating Schedule

A laminating schedule outlining the materials and order of operations required were established for each test. Reinforcement Materials, Infusion Materials and Resins were laid into the mould

Sample 1			
Layer	**Specification**	**Dimension**	**Comment**
1	Mould		Release agent applied
2	3 x CSM 450 g/m^2	700 x 200	
3	Release Film A2200	750 x 250	
4	Infusion Mesh Vi1	750 x 250	
Sample 2 Layers 1-3 as Sample 1			
4	Infusion Mesh Vi5	750 x 250	
Sample 3 – Layers 1-3 as Sample 1			
4	Infusion Mesh Vi2s	750 x 250	
Sample 4 Layers 1-3 as Sample 1			
4	Infusion Mesh Vi2	750 x 250	
5	Vacuum Bag		To cover all 4 samples
Resin and Vacuum lines central with spiral artery along length of mesh			

Table 3.5 Laminating schedule for initial trials

A range of materials exist to act as a release fabric but to also promote the flow of resin into the laminate from the infusion mesh.

Initial trials used A220 perforated release film specified for infusion use, alternatives to release films within the industry are porous peel ply materials which allow resin to pass through but do not adhere to the cured laminate. Initial trials showed the effectiveness of each release fabric.

Observations were made at the mould surface comparing the flow front across the infusion media to the flow at the mould surface as seen in Figure 3.7 Flow front through an infused laminate This gauged the rate at which the resin penetrated through the release media and layers of fibreglass.

Results compared the resin flow at the flow media side of the mould to the rate at which it flowed at the mould surface. As each release media was either perforated or allowed resin to pass through, tests determined which of the media was most effective. Tests were conducted with the range of media in Table 3.1 Infusion Media.

Figure 3.7 below shows the 'lag' between the resin flows on the top surface (Flow Front) compared to the mould surface (Mould Front). This lag was caused by the delay of resin passing through the release media and reinforcement materials until it reached the mould surface. The mould in this instance was a glass sheet which allowed the flow to be observed at the mould surface as well as through the vacuum bag and thus a comparison made between them.

For consistency all samples consisted of 3 layers of 450g/m^2 CSM infused with Encore 30 Polyester Resin

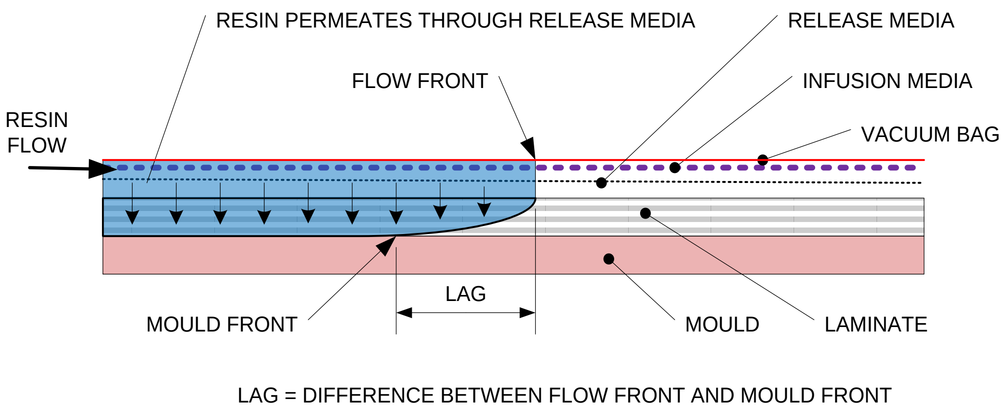

Figure 3.7 Flow front through an infused laminate

3.4.2 Preliminary results

The rate of resin infusion across the infusion media was determined by measuring the distance travelled by the flow front over time, at each time interval a line was scribed along the vacuum bag surface, results shown in Figure 3.9 reveal the rate of infusion for four different infusion meshes. Monitoring of any excessive exothermic reaction and observation for gassing of resin between laminates was monitored until the samples reached Gel point. Microscopic study (x200) revealed full infusion of fibres throughout the laminate. Figure 3.8(a) and (b) show a cross section through a test samples revealing that 7, 9 and 13 plies of laminate have successfully infused with no apparent voids or areas of resin starvation. Multiple slices were taken across the length of infusion and infusion appeared consistent throughout the laminate.

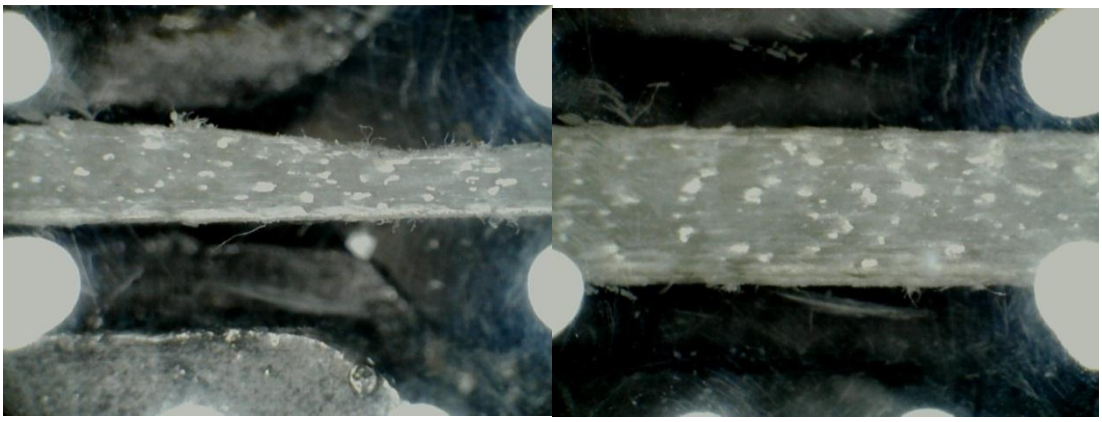

Figure 3.8 cross section 7 to 9 layers CSM (a) And (b) 13 laminates CSM

All samples infused successfully with no apparent voids or areas of resin starvation. Figure 3.9 shows that the rate of infusion differed depending on which infusion mesh was used. The coarser meshes Vi2 and Vi2s infused at a quicker rate and infused the full distance across the mould before the other meshes had completed, hence the flat-line at the top of the graph for these samples. This clearly demonstrated that the rate of infusion could be controlled within a mould depending on which infusion media was used.

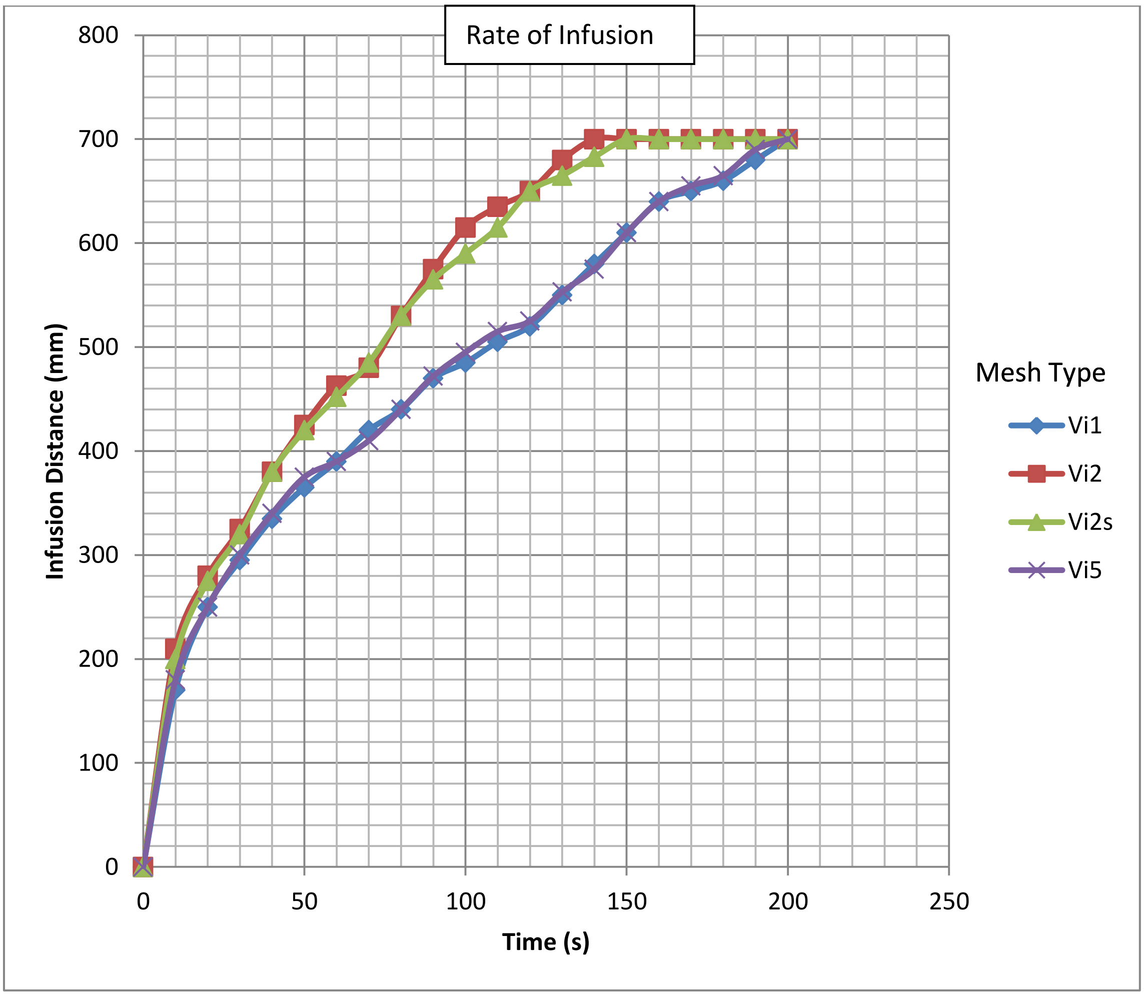

Figure 3.9 Infusion Media Trials – Rate of Infusion

Infusion meshes Vi1 and Vi5 infused at a slower rate, they were less stiff and had a finer mesh density, being less stiff makes them deform more under vacuum reducing the cavities through which resin could flow, the finer density of the mesh also gave a smaller overall flow area hence a slower flow rate..

The initial rate of infusion is shown to be higher initially. This can be attributed to the differential pressure between inlet and outlet changing as infusion takes place. As resin is released into the mould the pressure differential between the inlet and outlet is at its greatest therefore the infusion is quicker, moreover, since the resin pot is exposed to atmospheric pressure as soon as it is released the pressure differential drops over time.

Figure 3.10 shows that fibre volume fraction was consistent along the length of the infused samples with minimal deviation. Similarly no evidence of trends towards resin rich areas at the beginning or end of infusion was evident with each sample remaining consistent.

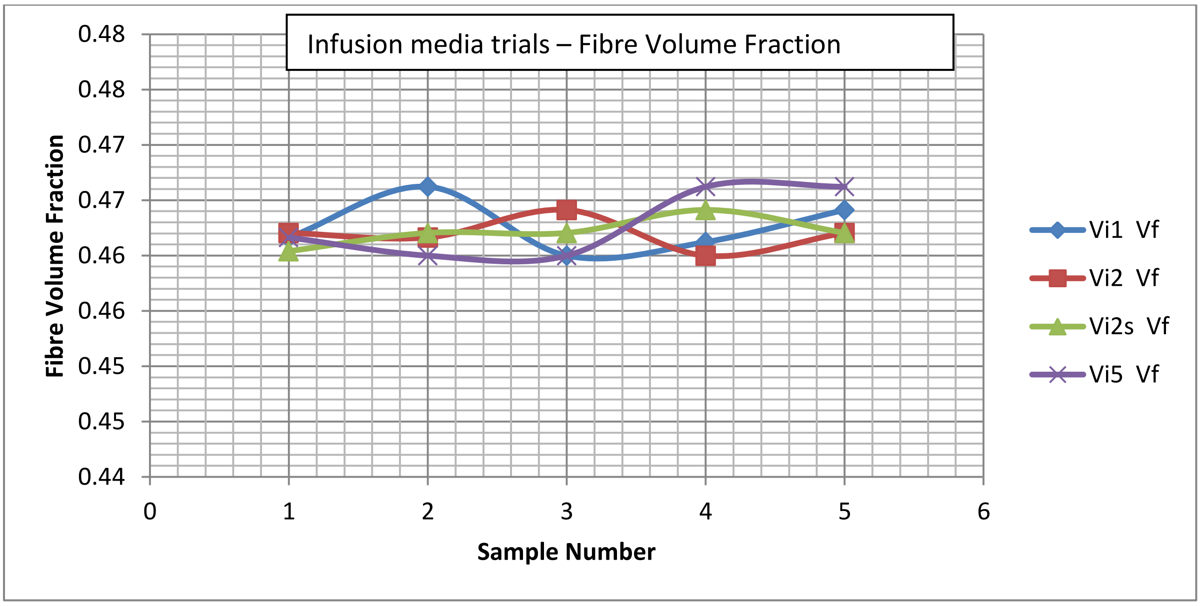

Figure 3.10 Media Trials Fibre volume Fraction

Unexpectedly the infusion rate did not appear to affect fibre fraction, initial thoughts were that a slower rate of infusion may lead to more resin passing into the reinforcement. This would suggest that resin infusion inherently controls the amount of resin infused to a saturation point where it would then rather proceed along the infusion than saturate the reinforcement further.

Results in Figure 3.11 show infusion rate between the flow front and mould front shown and the differential between them. For a range of samples of release film this revealed what influence the release media had on the lag between the two flow fronts. The lag is shown as the differential between the two fronts.

There was no evidence of resin starvation or resin rich areas in any of the samples suggesting that complete infusion had taken place. All samples released from the release film successfully suggesting no adverse effect on them.

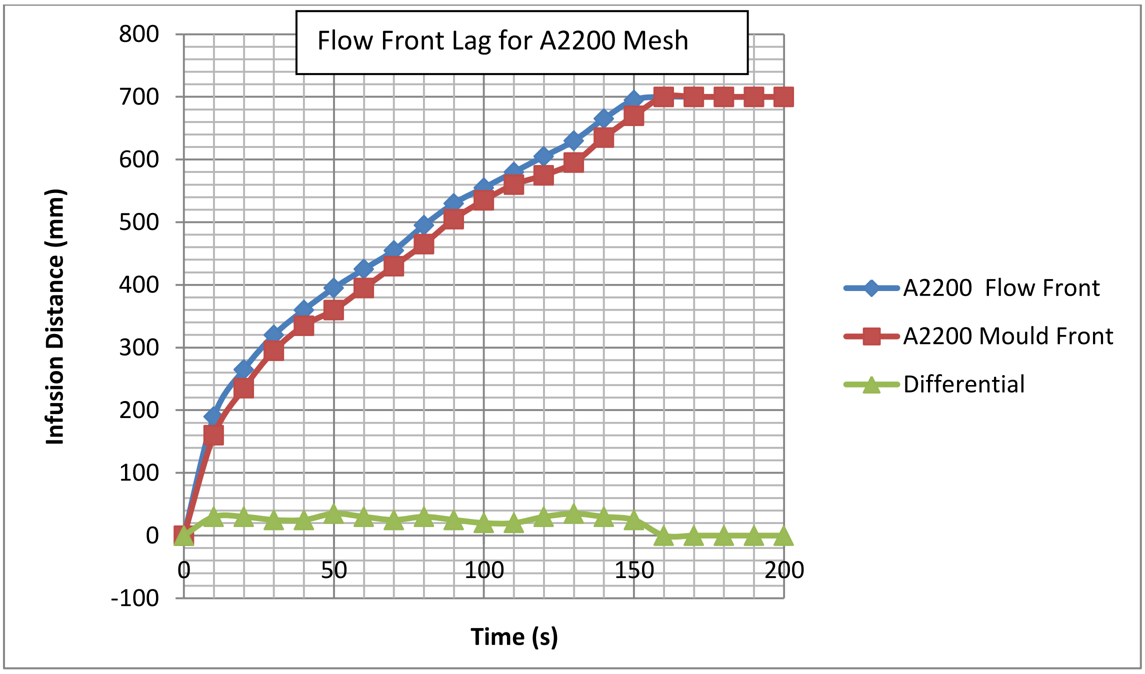

Figure 3.11 Flow Front Lag for A2200 Infusion Mesh

Results indicate that lag remained relatively consistent within a 20-30mm tolerance indicating that the lag remained consistent. Even when the flow rate declined due to pressure differential drop the lag remained relatively consistent.

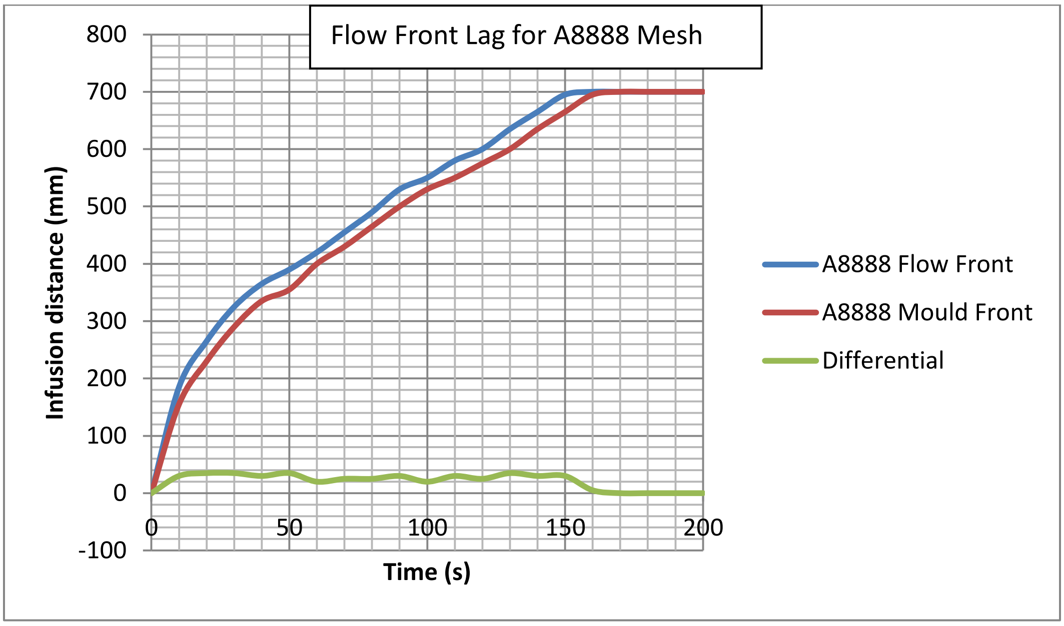

Figure 3.12 Flow Front Lag for A8888 Infusion Mesh

Figure 3.12 shows the differential across the flow front using the A8888 mesh, the lag remained constant throughout the infusion. The flow differential for a range of media is shown in fig 3.13 where all media show a differential but within a 20-40mm band. The comparative flow front differential for the three different release media used show very little difference in lag for each of the release materials used suggesting that release films/media have little effect on lag.

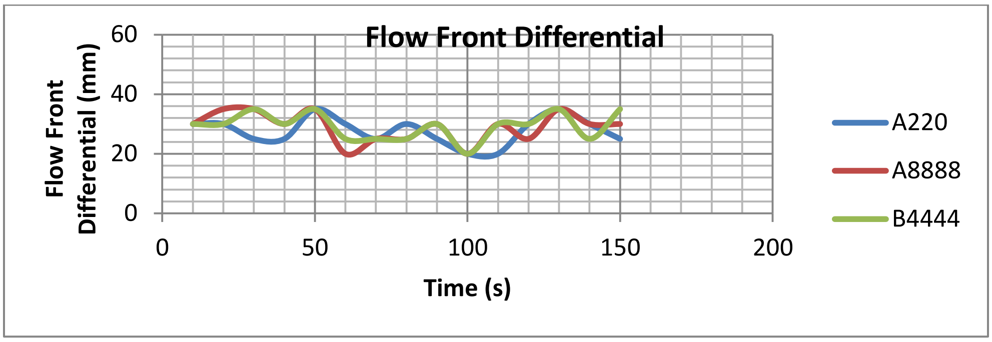

Figure 3.13 Flow Front Differential for all Media

Being evident that lag occurs and as observation of the mould surface is often not possible this factor must be considered to guarantee full infusion. If a lag distance for a particular infusion is known then a period of infusion after the resin has reached the outlet must be continued to ensure full infusion.

Results show the differential between the flow front across the top infusion media compared to the mould surface flow front. As expected there is a lag between flow fronts for an increase in ply thickness as the resin has to permeate through more layers to get to the mould surface.

Figure 3.14 shows the rate of infusion for a range of laminate thickness. Results suggest there is a direct relationship between the number of plies in a laminate and the lag at the mould surface. Results are consistent and decay as the infusion continued due to pressure differential change as described earlier.

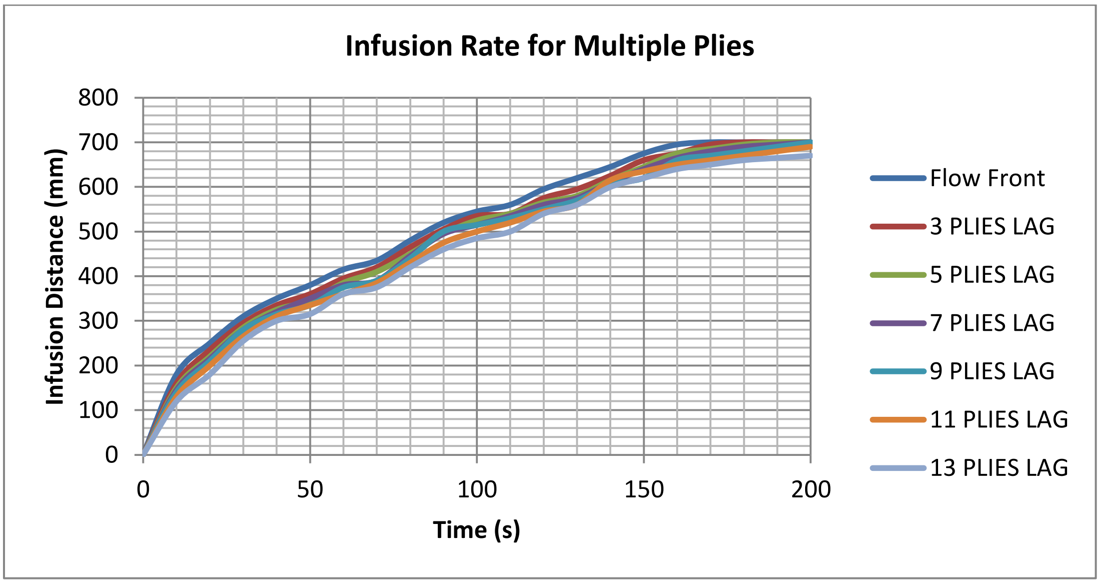

Figure 3.14 Flow Front Lag – Multiple Plies

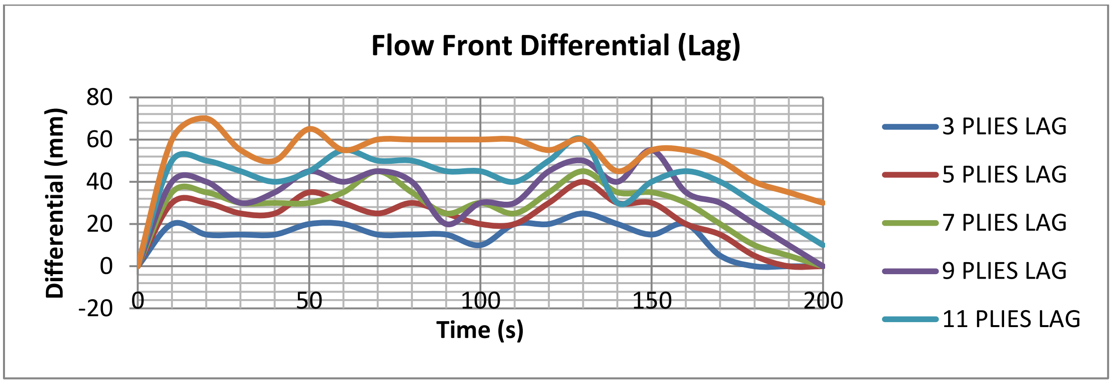

Figure 3.15 Flow Front Differential – Multiple Plies

The differential between flow fronts for multiple plies is shown in Figure 3.15 There is a clear correlation between the number of plies in a laminate and the lag. This appears logical in that as resin permeates through the release media into the laminate it has more material thickness to travel through before reaching the mould surface.

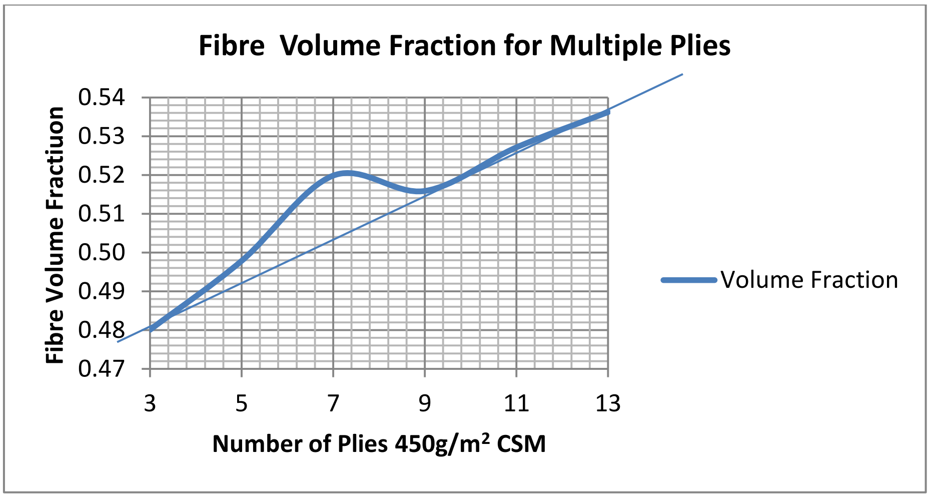

Figure 3.16 Flow Front Differential – Multiple Plies

Volume fraction measurements revealed a trend for a greater fibre volume fraction for an increase in ply thickness as shown in Figure 3.16 Although the volume fraction for any of the samples would be considered adequate and that full infusion had taken place. This suggests that to achieve a consistent fibre fraction for a component of multiple laminates the rate of infusion would have to be slowed down for thicker plies.

3.5 Summary

Trials served to show the vacuum infusion process to be repeatable and with predictable outcomes, complete infusion of samples with acceptable fibre fractions were produced. A range of infusion media revealed different rates of infusion could be achieved and flow across the laminate could be controlled to some extent allowing areas of a mould to infuse at different rates during a single infusion. Infusion of multiple laminates showed that fibre fraction increases with the number of layers within the laminate.

Observation of lag between the flow front and mould front showed a distinct relationship between the number of plies in the laminate and the lag between the fronts with the lag increasing as the number of laminates increased

Chapter 4 Materials and methods

Having proved the vacuum infusion process and gained experience of a range of infusion meshes and release films, the next stage was to conduct trials to compare materials specific to the vaccum infusion process and reinforcement commonly used in the wind turbine industry this was then be employed manufacturing small wind turbine blade skins within a mould. This required the manufacture of two moulds. Low viscosity epoxy resins and typical reinforcement used within wind turbine manufacture were specified for trials.

This chapter shows the range of trials conducted

4.1 Prototype blades

Initial infusion trials were carried out on a flat surface however full wind turbine blade moulds were required for analysis of infusion through a complete blade section. A blade 'plug' was manufactured. The plug served as a master shape off which the mould was taken. The plug had to be geometrically correct and have the surface finish required for the finished part.

Figure 4.1 Plug and Mould 1m and 2.5m Blades

4.1.1 Mould manufacture

The manufacture of the moulds furthered understanding and appreciation of the requirements of mould making and the processes required to go from a CAD model to a composite mould. Consideration to the infusion process and the requirement of a suitable flange for vacuum bag sealing was also given.

Two moulds were manufactured, one taken from an existing 1m blade and another later produced from a 3D CAD model. The 1m blade was prepared with horizontal flanges along the leading and trailing edges to allow one mould half to be laid up. Once cured the laid up half remained in place. Flanges were removed then the second half of the mould laid up to mate the existing mould flange face.

Figure 4.2 3D CAD Model 2.5m Blade

For the 2nd mould an existing CAD model of a prototype 2.5m blade was obtained (Figure 4.2) this model was created as part of the ISWindTech group at UCLAN. Created in Catia V4 and imported in IGES format.

Plugs were manufactured by dtbs (www.dtbs.co.uk) and CNC routed from MDF with 0.5mm allowance for surface coating. To facilitate manufacture of the mould flanges the 3D CAD model was split along leading and trailing edges and a horizontal flange created at the split line. Figure 4.1 shows the 2.5m MDF plug in its finished state with a painted and polished surface. Adjacent to it is the blade mould half taken from the plug. The large flange created facilitated the use of vacuum infusion. Moulds were manufactured using conventional wet lay-up techniques then post cured to 80 degrees to suit post curing of epoxy resin.

4.1.2 Specific reinforcement materials

Whilst initial tests were successful with general reinforcement and resins, materials used within the industry had to be researched; hence sought and sourced. This included low viscosity epoxy resin specifically developed for resin infusion.

The resin selected was Sicomin SR 8100 for the following reasons:

- Low exotherm - compared to general resins enabling thick laminates to be infused in a single process without excessive heat build-up during the curing of the resin.
- Low viscosity - The flow of resin through porous reinforcement under vacuum is improved with lower viscosity enabling the resin to permeate through the fibres easer
- Range of hardeners – fast or slow cure hardeners were available for the production of small or large components, giving longer infusion times with reduced risk of resin gelling.

Reinforcements commonly used in blade skin manufacture were sourced. (Fig 4.3) The commonly used Biaxial and Triaxial cloths are preferred, not just for their mechanical properties but knitted fibres in comparison to woven fibres allow better infusion of fibres in comparison. These cloths were found to have good drapability compared to CSM and woven roving

Reinforcement	g/m^2	Orientation	Supplier
Biaxial E Glass	310	+45 /-45^0	PRF Composites
Biaxial E Glass	600	+45 /-45^0	PRF Composites
Triaxial E Glass	793	+45/90/-45^0 (50% @ 90^0)	PRF Composites

Table 4.1 Fibre-glass used in trials

Release film with larger holes for infusion through to laminate was sourced, although not exclusively for infusion was considered a better release film compared to the perforated films commonly used in pre-preg lamination used in initial trials. Peel ply was also sourced through which resin could flow but still release.

Infusion trials were conducted in a similar manner to initial trials on a flat surface mould. Bi-Axial fibreglass and the use of an epoxy resin developed specifically for RI and RTM processes were used.

Figure 4.3 shows the set-up with samples isolated from each other although both sharing the same vacuum pump providing identical conditions for each sample thus comparable results

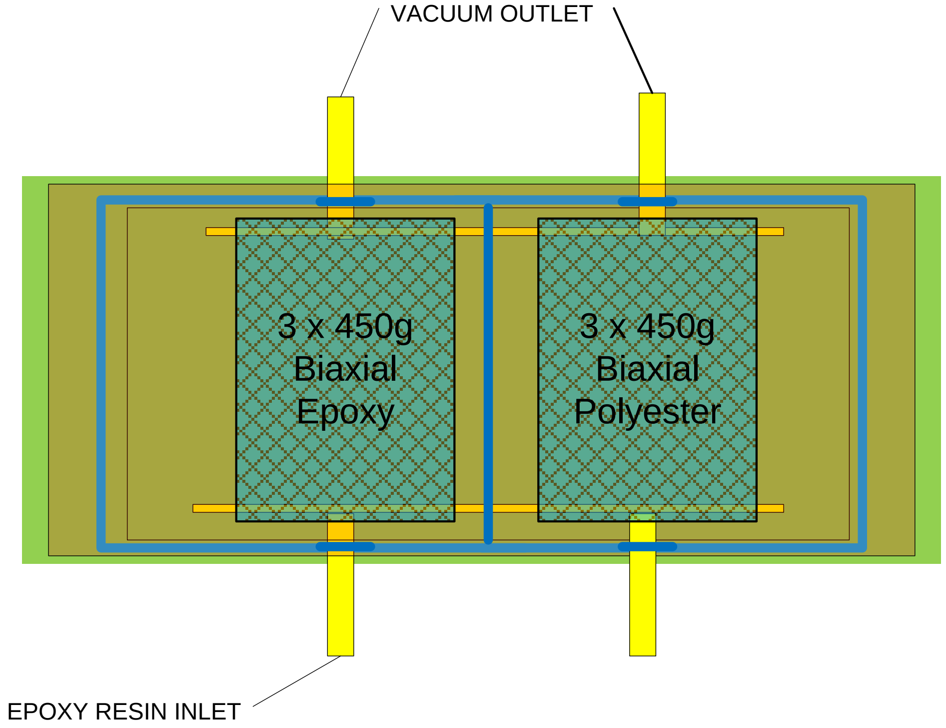

Figure 4.3 Matrix Trials

4.2 Foam core experiments

Core materials form part of many composite components. Sandwiched between laminates of reinforcement they serve to increase stiffness/weight ratio and increase the second moment of area. Skins of blades and spars often contain foam core structures. The ability to infuse with foam core sandwich is critical hence a range of methods were employed to determine an effective repeatable process.

Initial foam core trials were carried out using sheet PU foam sandwiched between a range of fibreglass reinforcement. Infusion media was introduced to the top surface with no media at the mould surface. Foam thickness of 3, 10 and 25mm were investigated. To observe resin flow at the mould surface test samples were created within a vacuum bag rather than up against a mould surface.

Further trials were conducted on slotted foams and in particular Rhoacell Polymethacrylimide. Trials were conducted on samples from 10mm and 25mm foam sheets. Infusion was carried out with and without infusion media on the top surface to observe the differences.

With some industrial infusion foams offered with holes through the section, trials were also conducted on foam cores with a range of custom hole patterns and spacings to observe their influence in the infusion process. To further assist flow at the mould surface channels were scored between holes.

Lag was measured on some samples comparing the flow front at the mould surface when the infusion was complete on the top surface similar to previous trials

Microscopic observation on sections was carried out revealing the consolidation of the reinforcement onto the foam and how resin passed fully through the foam channels and holes to the mould surface.

4.3 Blade skin experiments

Given the success of early infusions and with specific resins and reinforcement available, tests to create 2.5m blade skins were conducted. Initially tests with multiple layers towards the root and no core or spar cap were conducted, leading to foam cored skins with integral spar cap. Figures 4.4 (a) and (b) show examples of blade skins made.

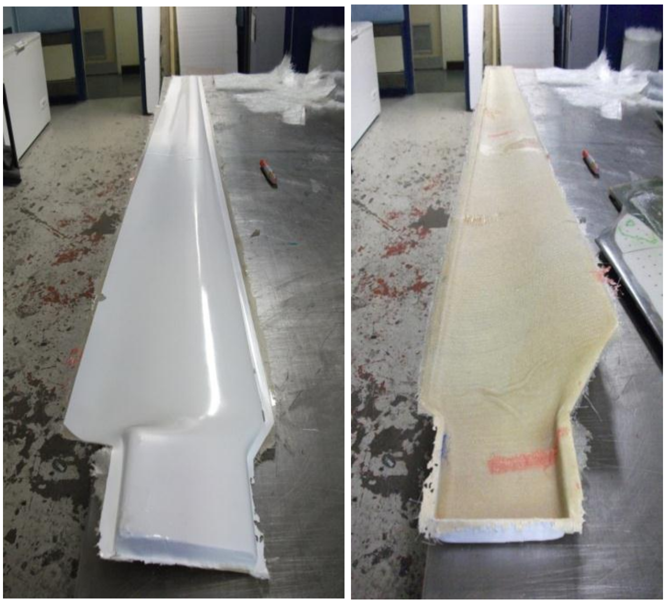

Figure 4.4 (a) Blade skin mould face, (b) Blade skin vacuum bag face

Initial tests attempted to infuse from root to tip in a single infusion. Further trials experimented with the location of resin inlet and vacuum outlet ports with multiple ports along the length of the blade. Infusions were also conducted across the width of the blade and from the centre of the blade towards the leading and trailing edges. Further trials looked at blade skins with an integral spar cap (stressed skins).

Tests were conducted in order to investigate whether multiple ply laminates could be infused along the entire length of the blade. The spar cap and any foam core sandwich materials were not considered at this stage. A range of inlet and outlet positions were tested with the same laminate schedule and fibre fraction tests conducted at each laminate thickness along the blade

4.3.1 Laminating schedule

To ensure consistency across each blade sample, a laminating schedule was developed for each test outlining the material for each layer in the structure of the blade and its dimensional placement along the blade length.

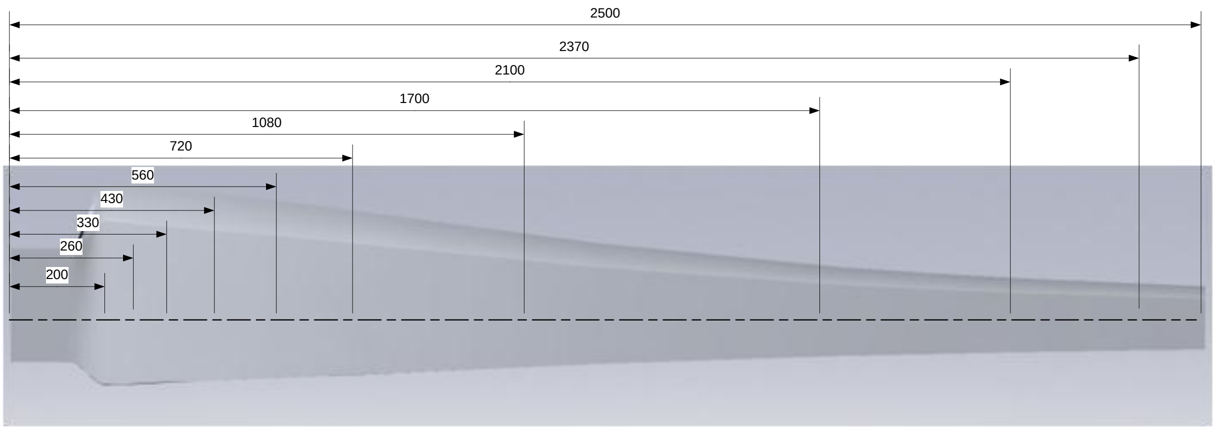

Figure 4.5 Dimensions for reinforcement placement along 2.5m blade length

Layer	Specification	Dimension	Comment
1	Gel Coat	Whole Blade	Pigment White 10%
2	Biaxial 450g/m^2 EX203	2500	
3	Biaxial 450g/m^2 EX203	2500	
4	Biaxial 450g/m^2 EX203	2370	
5	Biaxial 450g/m^2 EX203	2100	
6	Biaxial 450g/m^2 EX203	1700	
7	Biaxial 450g/m^2 EX203	1080	
8	Biaxial 450g/m^2 EX203	720	
9	Biaxial 450g/m^2 EX203	560	
10	Biaxial 450g/m^2 EX203	430	
11	Biaxial 450g/m^2 EX203	260	
12	Biaxial 450g/m^2 EX203	200	
13	Biaxial 450g/m^2 EX203	200	

Table 4.2 Laminate Schedule 2.5m blade

4.3.2 Inlet and outlets

Different positions for the resin inlet and vacuum outlet were tested, each with the same laminating schedule shown in Table 4.7 This established the nature of resin flow through the laminate and highlighted any areas of starved resin or areas failing to infuse. Use of plastic spiral binding as a resin artery was employed in some cases.

Fig 4.6 shows one such test with the inlet at the centre of the leading edge with a spiral artery to deliver resin along the length of the blade and two vacuum outlets on the trailing edge with a spiral artery for collecting resin as it infused across the width of the blade. This established the nature of resin flow through the laminate and highlighted any areas of starved resin or areas failing to infuse.

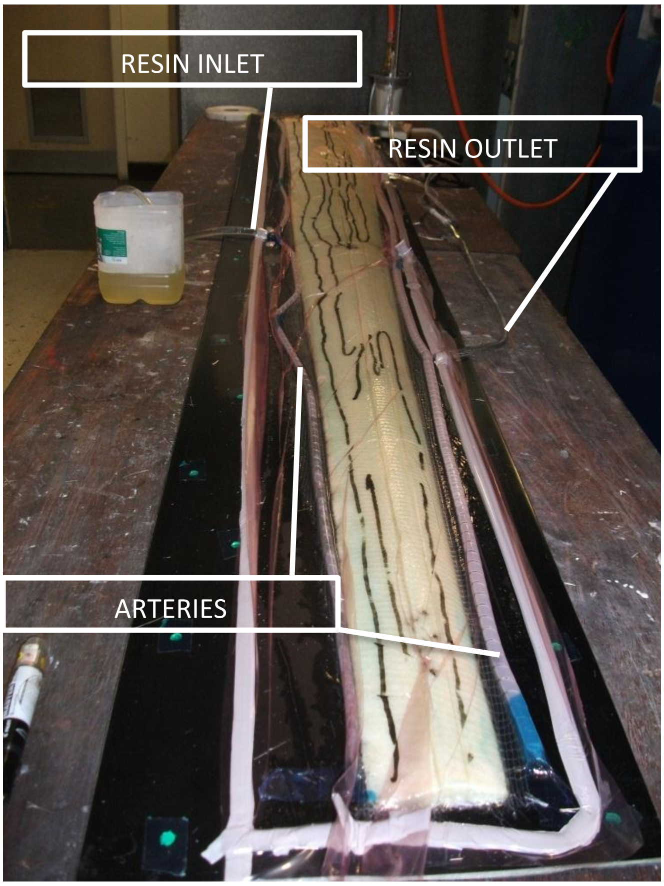

Figure 4.6 Resin Inlet and Vacuum outlet positions

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A range of inlet and outlet positions were trialled, Figure 4.7 illustrates one of the positions trialled, a single resin inlet is positioned mid way along the blade with a single vacuum outlet on the trailing edge. Spiral arteries were used to deliver resin along the blade length and also used on the outlet.

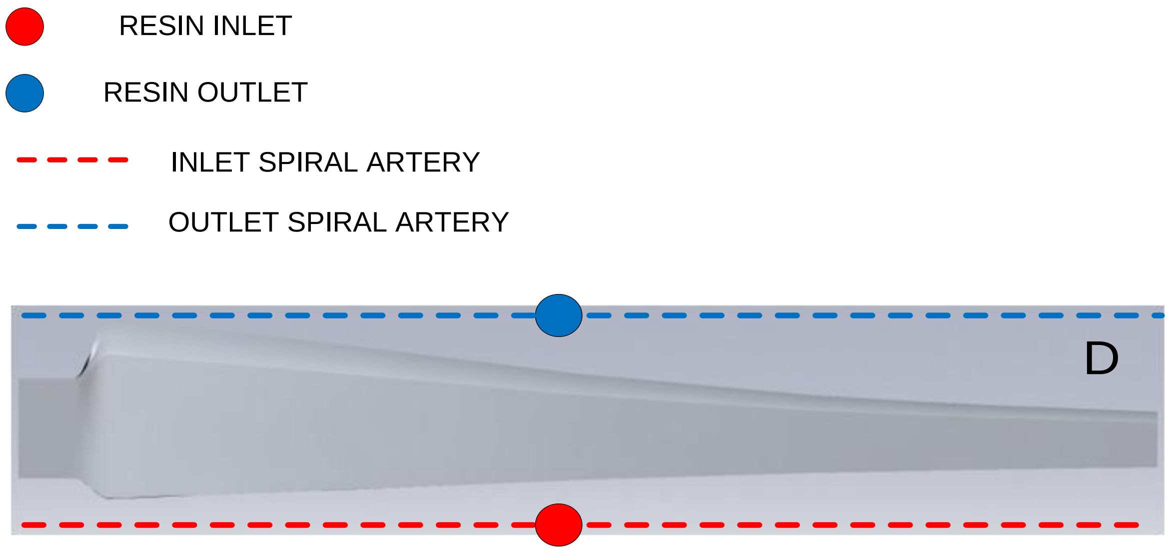


Figure 4.7 Graphical representation of inlet/outlet positions and spiral arteries

Tests were carried out using a range of inlet/outlet combinations with varying results. Time taken to infuse the full blade and observation of the nature of resin flow through the laminate were recorded. Figure 4.8 illustrated the range of inlet/outlet combinations attempted.

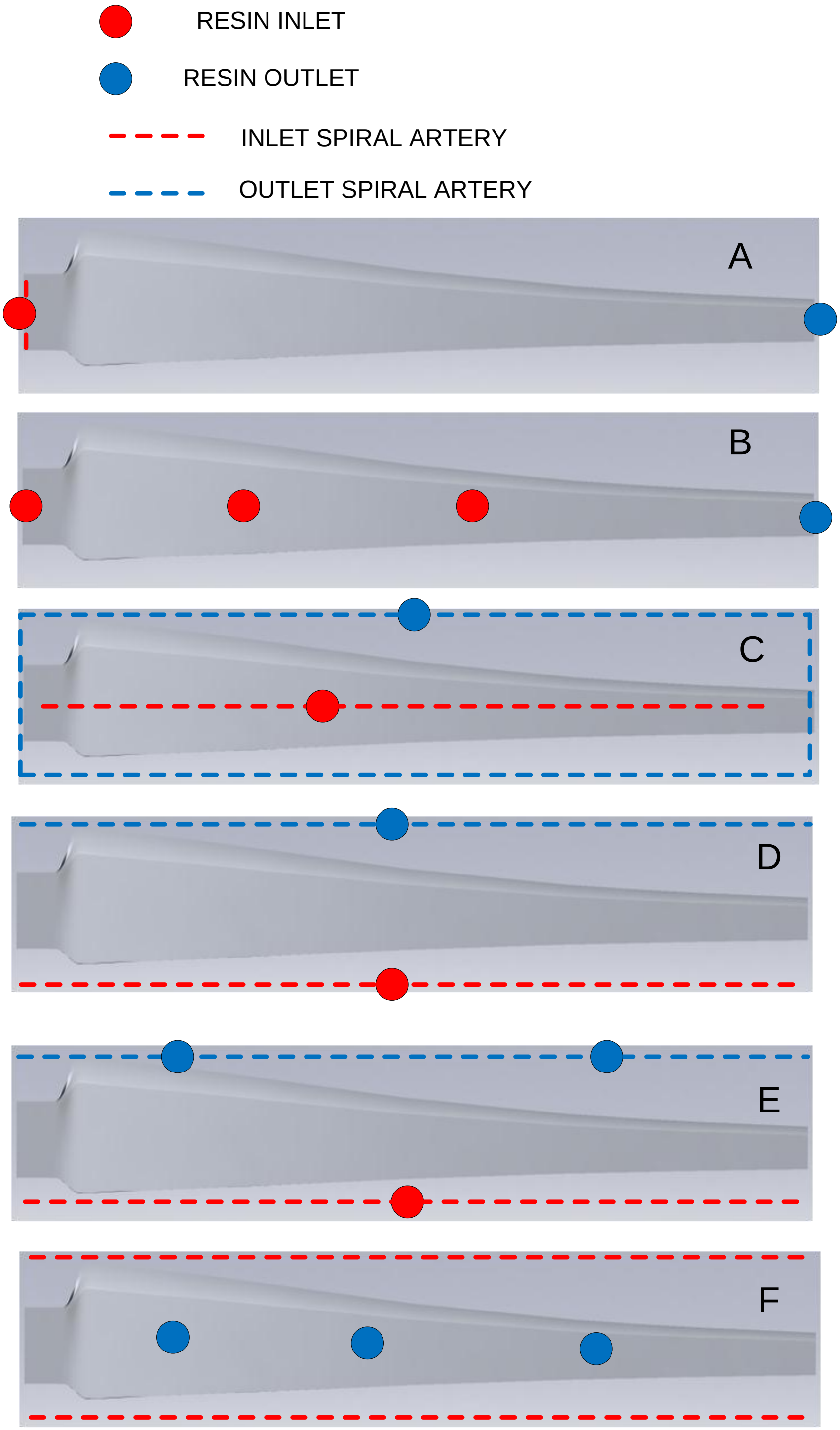


Figure 4.8 Locations of Inlet / Outlet and spiral arteries

4.4 Spar caps and foam core trials

With many blade skins having a foam core sandwich structure, trials turned to incorporating the findings from the infusion trials and foam core trials into manufacturing a stressed blade skin. The structure of the skin would consist of layers of fibreglass reinforcement sandwiching a central spar cap and incorporating 3mm foam core as shown in Figure 6.1

Figure 4.9 Section through stressed skin

This shows a section through an infused skin with foam core and spar cap evident. The spar cap is almost all unidirectional fibres with the skin being a single layer of 450g/m^2 Biaxial E Glass either side. Foam core was tailored with holes 3mm diameter perforated at 25mm intervals, foam was shaped outside the spar cap region ending 15mm before leading and trailing edges. The foam was chamfered 45^o at leading and trailing edges to assist consolidation and prevent a resin channel forming.

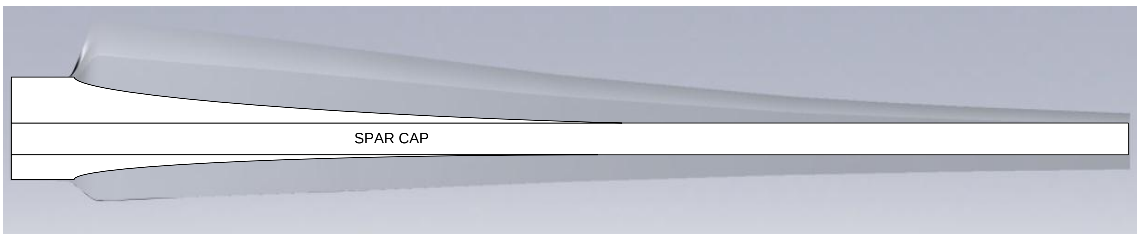


Figure 4.10 Spar Cap Region

Following full blade trials, method E was used to ensure a consistent infusion with resin inlet and vacuum outlet positions deployed as shown in figure 6.1.2

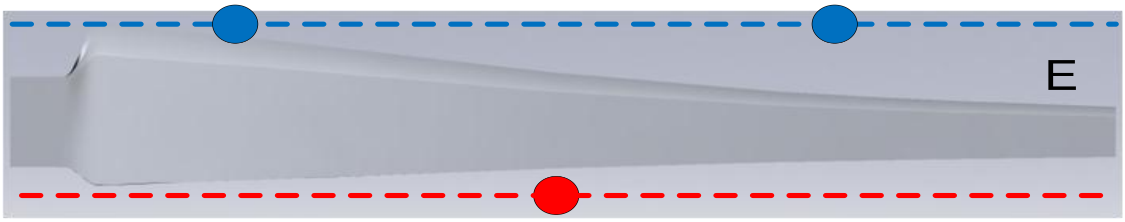


Figure 4.11 Infusion Method E – Inlet/Outlet position

4.4.1 Laminate schedule

To achieve a consistent laminate as schedule was created to determine what plies of reinforcement would be placed along the mould length, the following dimensions where points along the length of the blade where the laminate thickness or features changed and feature in the dimensions column in Table 4.3

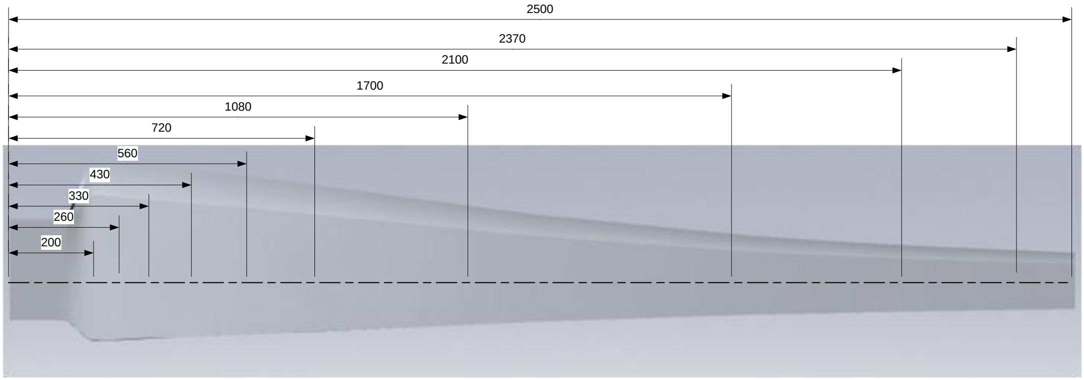


Figure 4.12 Laminate Dimensions for 2.5m blade

The following laminating schedule was used to produce the stressed skin:

Layer	Specification	Dimension	Comment
1	Gel Coat	Whole Blade	Pigment White 10%
2	Biaxial 450g/m^2 EX203	2500	
3	Biaxial 450g/m^2 EX203	2500	
4	Foam Core 3mm Acrylic	Outside spar cap region – 15mm inside leading and trailing edges	Perforated 3mm holes 25 x 25 spacing with 45^o chamfer at leading and trailing edges
5 -16	600 g/m^2 stitched UD 300g/m^2 biaxial every 4 plies UD	2500 2500 2370 2100 * 1700 1080 720 560 * 430 330 260 200 *	Spar Cap region only
17	Biaxial 450g/m^2 EX203	2500	
18	Biaxial 450g/m^2 EX203	2500	
19	Biaxial 450g/m^2 EX203	2100	
20	Biaxial 450g/m^2 EX203	1080	
21	Biaxial 450g/m^2 EX203	720	

Table 4.3 Laminate Schedule – 2.5 m stressed skin blade

4.5 Custom resin channels

Initial tests using commercially available slotted foam core materials revealed the tendency of the slots in the foam to act as resin channels under vacuum and without the use of infusion mesh. Considering that channels on the surface of a core material could act to irrigate resin and potentially direct it, several experiments were conducted to examine this.

Incorporating custom channels into an aerofoil section enabled the observation of the infusion process over a typical blade section as well as through the structural spar element of the blade.

With channels in foam acting as a conduit for resin under vacuum, tests were conducted without the use of infusion media to establish the effectiveness of channelling to control and direct resin.

The setup for these trials is shown in Fig 4.13 which consists of an aero section foam core scored with irrigation channels infused between layers of biaxial glass with epoxy resin. The trace of the custom channels can be seen through the vacuum bag.

Figure 4.13 Set-up for infusion of aero section

Aerofoil sections manufactured from extruded polystyrene were manufactured to represent a typical cross section of a wind turbine blade. Tests were conducted with the section and all reinforcement inside a vacuum bag to observe the resin flow at each surface. Reinforcement consisted of two layers 450 g/m^2 Biaxial Fibreglass. Channels were created at a range of angles and spacing and infused at 90^o (end to end) or 0^o (leading edge to trailing edge) Figure 4.14 shows the direction of the channels from Leading Edge (LE) to Trailing Edge (TE)

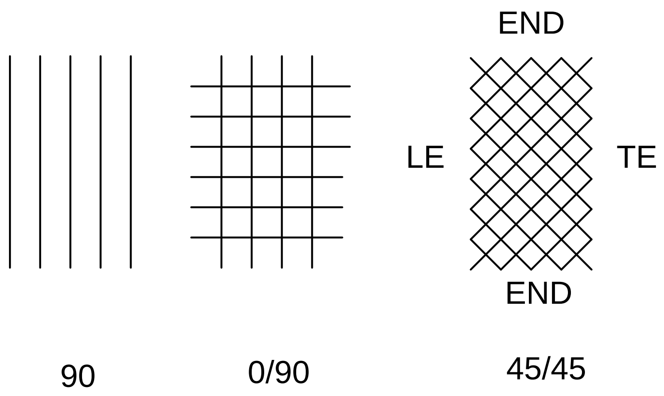


Figure 4.14 Custom channel patterns

Table 4.4 gives the channeling placement for the trials corresponding to Figure 4.14 detail. The range of channeling and angles allowed the charecteristics of each to be observed

Trial	Angle	Spacing
1	90	25
2	0/90	25 x 25
3	0/90	25 x 25
4	45/45	25 x 25
5	45/45	25 x 25
6	30/30	25 x 25
7	60/60	25 x 25

Table 4.4 Custom channel angle and spacing

4.6 Spar section investigations

The structural spar element of a blade was also considered as essential in satisfying one of the main aims of this research. With spar designs ranging from box-section cores to single or multiple webs, tests were conducted on foam aerofoil sections but with a range of shear web/spar geometries. Infusion of the samples examined whether the infusion could extend beyond the skin and included three-dimensional sections down the length of the wind turbine blade section.

Foam aerofoil sections were sliced along their length to create a range of single and multiple shear webs across the same section as shown in Figure 4.15. Without the use of any infusion mesh the infusion of resin relied on custom channels scored in the foam for irrigation of the resin. Channels would also be scored through the section to assist resin flow through the shear web. Infusions were conducted at both root-to-tip and leading edge to trailing edge with single inlet and outlet ports with +45/-45 custom channels 25mm spacing

Figure 4.15 Sliced foam core to give shear web

4.7 Full core infusion

The distinctive nature of flow through custom channels was further investigated by establishing custom channels and shear webs within a full size 2.5m foam core. Flow channels in a full length foam core enabled the control of resin across the skins but also through the spar section. Tests revealed the nature of flow across a complete blade section. Figure 4.16 shows one test during infusion with 80% of the blade infused.

Figure 4.16 full core infusion 1m blade

Polyeurethane foam cores were cast by pouring liquid expanding foam into blade moulds, this was done within the 1m and 2.5m moulds. Cores were then split along the spar section and the pattern of flow channels scored into the surface of the blade core. Trials were conducted initially within a vacuum bag rather than on the mould surface to observe resin flow along the full length the blade section. The laminate structure was kept simple to 2 x 450g/m^2 Biaxial fibreglass. A range of infusion and vacuum ports were tried including tip to root and across the width of the blade.

Different flow channels were introduced on either side of the blade core to observe any differences in the nature of flow through the channelled sections, this would determine whether the flow across the blade would mimic the flow observed during the aero section trials.

4.8 Half mould infusion

With the majority of tests being conducted on either flat surfaces or within a vacuum bag the issue of infusion within a mould was addressed. Observation of resin flow at the mould surface had previously be attained by the use of glass but could not be observed through a GRP mould. Using one half of the blade mould with the other half under vacuum bag allowed observation of resin flow across the top surface. Fig 4.17 shows a half mould infusion setup with the upper surface of the mould being replaced by vacuum bag to observe resin flow path.

Figure 4.17 Half mould infusion setup

Flow channels were created on a full blade core with the angle of the channel reducing towards the tip attempting to balance the infusion rate from leading edge to trailing edge. A single resin inlet was created at the centre with an artery along the leading edge, an exit artery ran along the trailing edge with two vacuum outlets with the capability to seal either if resin flow was quicker across the narrower section. Resin channels were created on the mould surface side and omitted from the vacuum bag side to limit the influence of one side over the other.

Chapter 5 Results

A great range of trials were conducted from simple infusions on a flat surface to complete blade skin infusions. Observation of the flow of resin through the components was achieved either by using safety glass as the mould surface or by using the vacuum bag itself to observe flow. Some microscopic study was done to examine sections through infusions.

5.1 Initial Trials

Although trials were limited to general laminating resins and fibreglass reinforcements, initial trials were successful in demonstrating the process and developing technical competence. It also highlighted the temperamental nature of the process if conditions and set-up were not wholly correct.

Consistency of the resin fraction was evidently very good and proved the effectiveness of the process and its potential to achieve a level of consistency across a component.

The infusion rate did not appear to affect fibre fraction, suggesting that under vacuum the reinforcement has a level of permeability which cannot easily be exceeded.

Release material trials revealed that each of the three materials performed similarly with no distinct advantage or limitation between them. The only issue was surface finish at the laminate.

The slight increase in fibre volume fraction for thicker laminates was attributed to:

Compaction of the reinforcement. Although the reinforcement is subject to the same pressure differential as thinner laminates, its compaction may be less overall thus easing flow of resin through the fibres.

Infusion rate. Whilst laminate thickness differed, the flow across the top flow media was equal for thin and thick laminates, a slower media was deemed most effective to creating full infusion across a thicker reinforcement layer.

The range of infusion media available gave some control over the rate of infusion giving the option to place different types of media where flow needed to be focused or regulated, similarly having no flow media had a dam effect almost halting flow compared to flow across the media.

Any loss of vacuum or air entering the mould via leaks were a common occurrence during initial stages and led to scrap samples.

Results revealed that the lower viscosity epoxy resin infused at a faster rate than the general purpose polyester resin with infusion being complete almost a minute earlier along the 700mm sample.

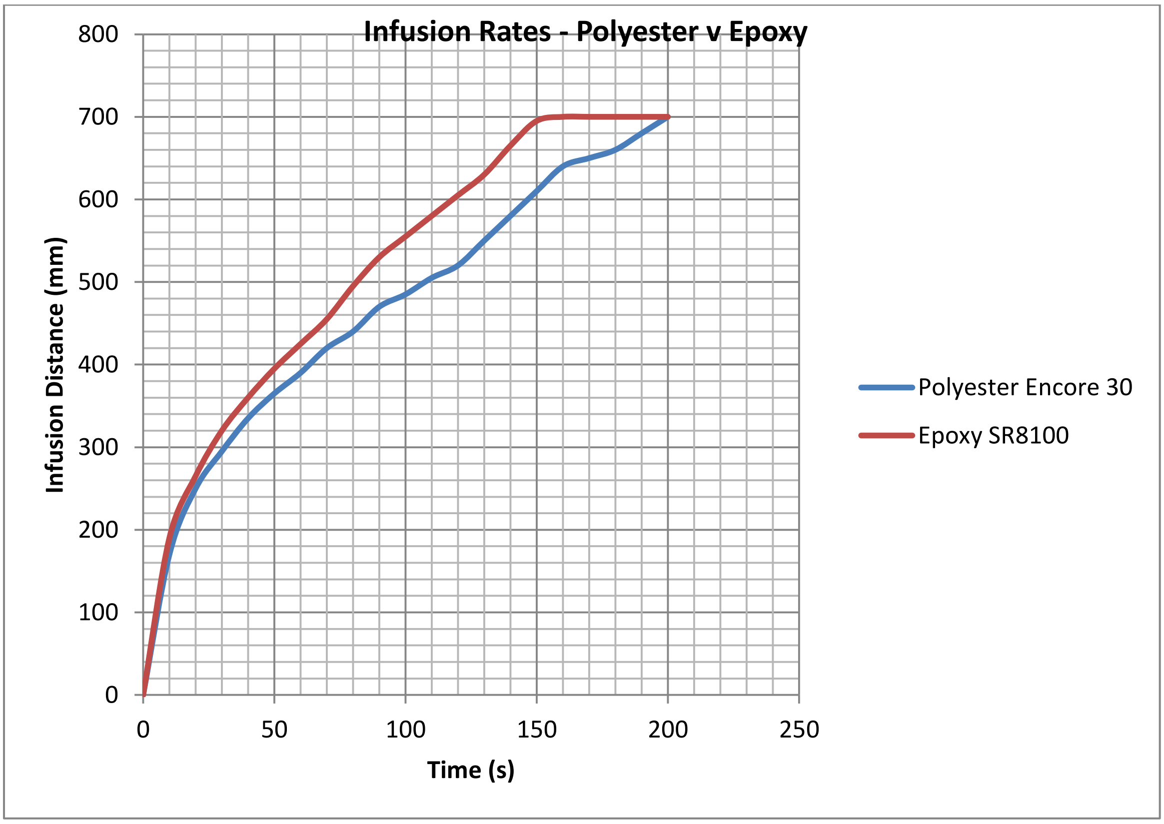


Figure 5.1 Infusion Rate Comparison – Matrix

5.2 Foam core and spar-cap

A stressed skin incorporating spar cap, foam core and multiple ply laminate structure was successfully infused. Holes in the foam core allowed transfer of resin to the mould surface and there was no evidence of voids or over saturation of the reinforcement materials.

5.2.1 Foam core infusion

The following hole spacing and channel patterns were trialled indicated in Table 5.1 Samples were two layers of 450g/m^2 Biaxial fibreglass each side of the foam core. The table lists the three foam thicknesses trialed, the spacing of holes and whether channeling between the holes was used.

Foam Thickness (mm)	Hole Spacing (mm)	Channeling
3	25x25	None
3	25x25	0/90
3	25x25	45/45
3	40x40	None
3	40x40	0/90
3	40x40	45/45
10	25x25	None
10	25x25	0/90
10	25x25	45/45
10	40x40	None
10	40x40	0/90
10	40x40	45/45
25	40x40	None
25	40x40	0/90
25	40x40	45/45

Table 5.1 Hole spacing and channelling trials

5.2.2 Custom foam

Results seen in figure 5.2 revealed that all infusions were successful and that a combination of holes and channelling could assist in the infusion at the mould surface. Significantly the samples with no channeling (NONE) took the longest to infuse indicating that channeling was an effective method of transferring resin through a laminate under vacuum. Although all tests eventually infused the 25x25 hole patterns infused at a faster rate than the 40 x 40 pattern. The graph shows an increase in lag as the foam thickness increased, this is predictable as resin had to pass through holes to mould surface and so has further to travel. Channelling in the foam reduced Lag with 0/90 performing best although there was a tendency for resin to travel quicker down the centre of the sample

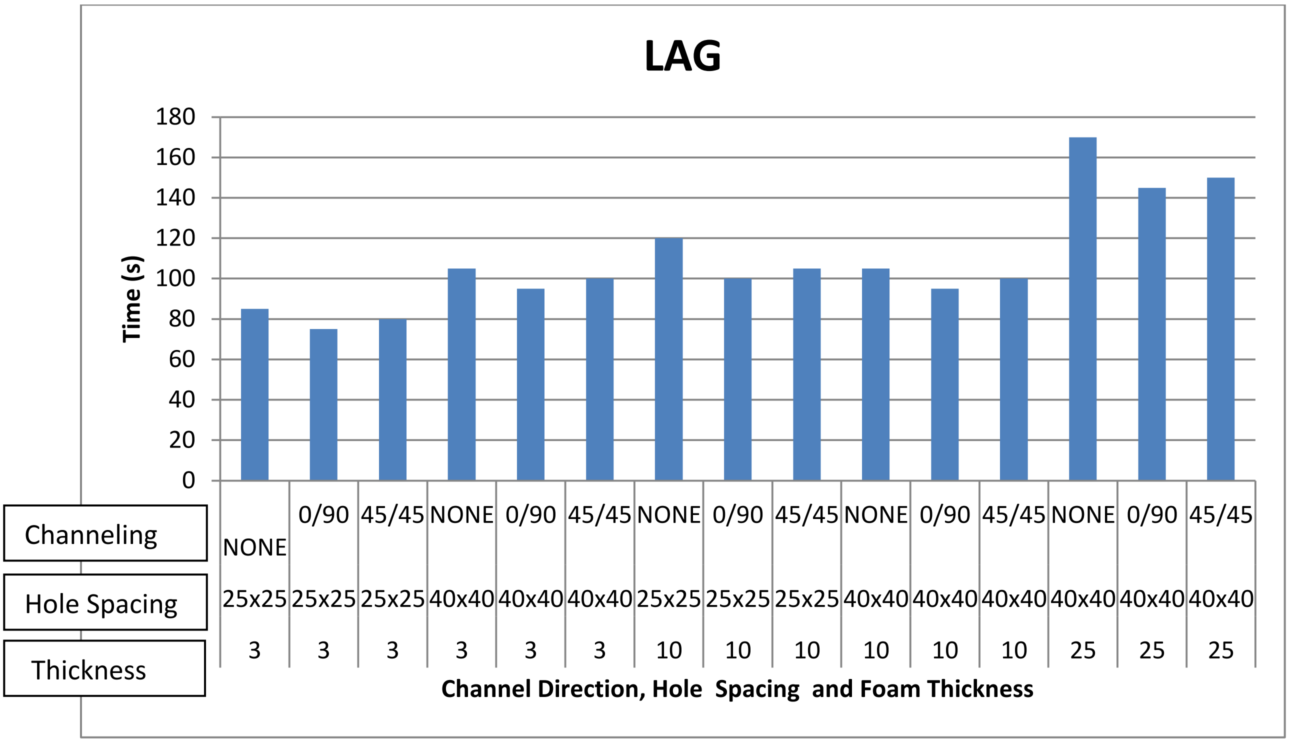
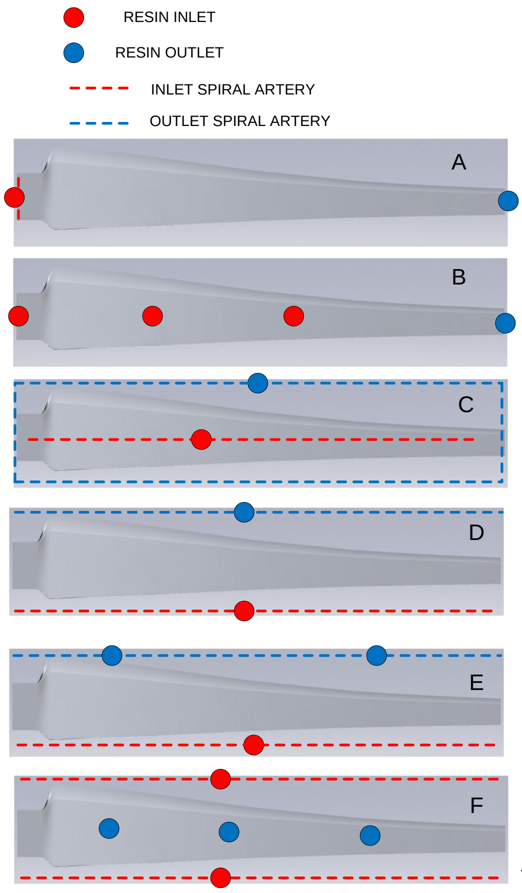


Figure 5.2 Lag across range of channelling, hole spacing and foam thickness

Infusion across the flow media was consistent with previous benchmark tests with the foam seeming to have no apparent influence on the media, however flow at the mould surface was often hindered or produced resin starved areas or did not infuse. Poorly consolidated sharp corners or radii in the foam cross section acted as resin channels for resin to flow at a faster rate than over the infusion media surface and produced resin rich areas Slotted foams revealed resin flowed freely along the slots. Flow was impaired in some samples and in some instances resulted in resin starvation at the mould surface. Depth of slots intended to allow foam to deflect around curves were discovered to sometimes create cavities which could affect the quality and strength of a component.

5.3 Laminations

Results showed that multiple laminates could be successfully infused along a blade length with laminates increasing towards the blade root. Placement of the resin inlet and vacuum outlets proved critical in achieving complete infusion. Each method also had an influence on infusion time. Table 5.4 reveals the results from each test with Fibre Volume fraction range across the laminate. The timing of each infusion is also included.



Tests A-F range of inlet/outlet positions

Test	Succesful)	Volume Fraction range	Time (min)	Observations
A	NO	-		Failed to infuse full length of blade, infusion progression became too slow, excess waste resin build up at root end
B	YES	0.35 - 0.50	17:00	Resin inlet time staggered, inlet opened as flow front reached port, high resin content at root and excess resin and marks in laminate at port locations
C	YES	0.40 - 0.50	08:30	Fast infusion, tip infused earlier than root leading to excess waste resin in trap
D	NO	-		Root failed to infuse correctly, resin transferred across blade to outlet quickly, excess resin in trap
E	YES	0.40 – 0.45	09:30	Even infusion, second outlet blocked off after tip infused assisting root infusion, minimal waste
F	YES	0.35 – 0.45	08:00	Quick even infusion, outlet pipes blocked off as resin reached them. Outlet ports left marks in laminate

Table 5.2 Inlet/Outlet positioning observation summary

5.4 Moulds and Tooling

A conventional two-piece mould was considered suitable. Channels for vacuum and resin could have been included but would be deemed ‘fixed’ and not allow for variation in inlet and outlet conditions during trials. MDF was very successful as an inexpensive medium for the plug. Minimal finishing of plug was required therefore the level of detail and surface finish required was achieved and with an acceptable level of accuracy. Mould could also be used to cast foam cores, inserts could be introduced to the mould to compensate for the laminate thickness along the blade length.

5.5 Matrix Materials

The infusion rate of the Epoxy over Polyester showed a significant increase in infusion speed but did not influence the infusion into the reinforcement. The low viscosity of the resin was key to this. Volume fraction samples revealed equal infusion across both samples

With its low viscosity, longer pot life and a range of hardeners available the Epoxy is superior to the Polyester resin trialled.

5.6 Foam Core Trials

Trials revealed what elements were required to successfully infuse a foam cored product and also revealed potential problems and quality issues.

Starved areas of resin on many early samples concluded some form resin transfer to the mould surface was required; the creation of holes through the foam facilitated this and proved successful as did the introduction of scored channels between the holes

Trials on industry available foams presented quality issues in that cavities could appear in the slot suggesting the slot depth to be a critical factor in promoting cavities but also for carrying excess resin.

5.7 Blade Skin Trials

Placement of inlet/outlet ports was critical in the timing and consistency of the resin infusion. Method E was most successful with a reasonable infusion time, consistent volume fraction and marginal waste. Method also ensured no marks left on the component after cure at port locations. Use of spiral artery most successful with even, controllable resin distribution.

The methods and findings of previous trials led to the ability to infuse complete blade skins and stressed skins complete with spar cap and foam core sandwich brought together. Location of inlet and outlet positions was critical with several failed infusions showing the complex nature of the process and the reason it can be dismissed by some manufacturers.

Microscopic analysis proved a good indicator of the success of the infusions revealing correct consolidation and permeation through the blade skin section.

5.8 Spar Section

Trials proved the creation of a central spar section within an aero section possible, shear webs were suitably bonded and consolidated to the foam core. Multiple shear webs could be infused in a single process again confirming that a full blade infusion complete with spar to be possible.

5.9 Flow Channel study results

Results from the flow channel experiments are given highlighting the effectiveness and direction of resin flow produed by them.

5.10 Custom resin channels

As the aero sections represented a cross section of a wind turbine blade with the skins at the surface of the vacuum bag it was vital to observe the nature of flow over the surface. The angle of the channels had a distinct influence on the direction and rate of infusion, particularly for aerofoil foam sections. Table 5.5 outlines the results.

Trial	Channel Angle (deg)	Spacing (mm)	Time (min)	Observation
1	90	25	13:30	Rapid flow ahead of the main resin flow front through reinforcement, slow infusion across channels in 0 direction – reached exit too early, excess resin in trap
2	0/90	25 x 25	12:00	As trial 1 however better flow in 0 direction, flow along 90 reached outlet too early
3	0/90	25 x 25	06:15	As trial 2 with no apparent advantage to infusing leading edge to trailing edge
4	45/45	25 x 25	10:30	Centre area infused slightly quicker than edges, infusion into channels distinctly apparent
5	45/45	25 x 25	05:00	As trial 4 with no apparent advantage to infusing leading edge to trailing edge
6	30/30	25 x 25	18:00	Slowest infusion rate, very even infusion across whole area
7	60/60	25 x 25	08:30	Centre area infused ahead of sides, flow into channels distinctly apparent

Table 5.3 Summary of trials with custom resin channels

Significantly the angle of the channeling appeared to have a direct influence on the infusion rate and therefore suggests that channeling in the foam core could control the infusion rate. The direct influence on the rate and direction of resin flow under vacuum has implications for manufacturing in that channeling would be able to control resin flow in the same way infusion mesh can, in denser areas of reinforcement, channeling could be modified to give an even infusion

Custom channelling within a foam core, or bladder, soluble core or any other method of creating internal cavities is seen as a distinct variation on utilising conventional foam sheets which tend to be horizontal and vertical slots which can be oriented differently.

To target areas requiring more or less resin or the need to control the rate of flow over one surface compared to another is proven to be feasible. The implications of this development lead to the understanding that components that prove difficult to infuse or with areas reluctant to infuse would benefit from custom channels.

The consistency of results leads to the thought that analytical study and simulation of custom channels is feasible with modelling with analogy to arteries and veins feeding the skin

5.11 Full Core Infusion

Infusion of a full blade core including the spar section was successful, the nature of the flow of resin across the blade skin and the top of the spar section was closely observed and seen to be consistent with earlier trials. Noticeably the infusion of the spar section appeared to keep pace with the skin infusion.

5.12 Half mould Infusion

This element of the project was considered most significant. The ability to infuse a full blade section complete with internal structure satisfied the main aim of the research. The combination of the custom channels and the placement of resin and vacuum points had a significant effect. One trial was conducted with no channelling on the bag surface but with channelling on the mould surface, the infusion was leading edge to trailing edge.

The significant outcome here was that the resin appeared at the trailing edge and up through the spar sections showing that resin had flowed under the core via the custom channels and across the mould surface. In contrast the top surface where the core had no custom channels the resin has only just infused the leading edge

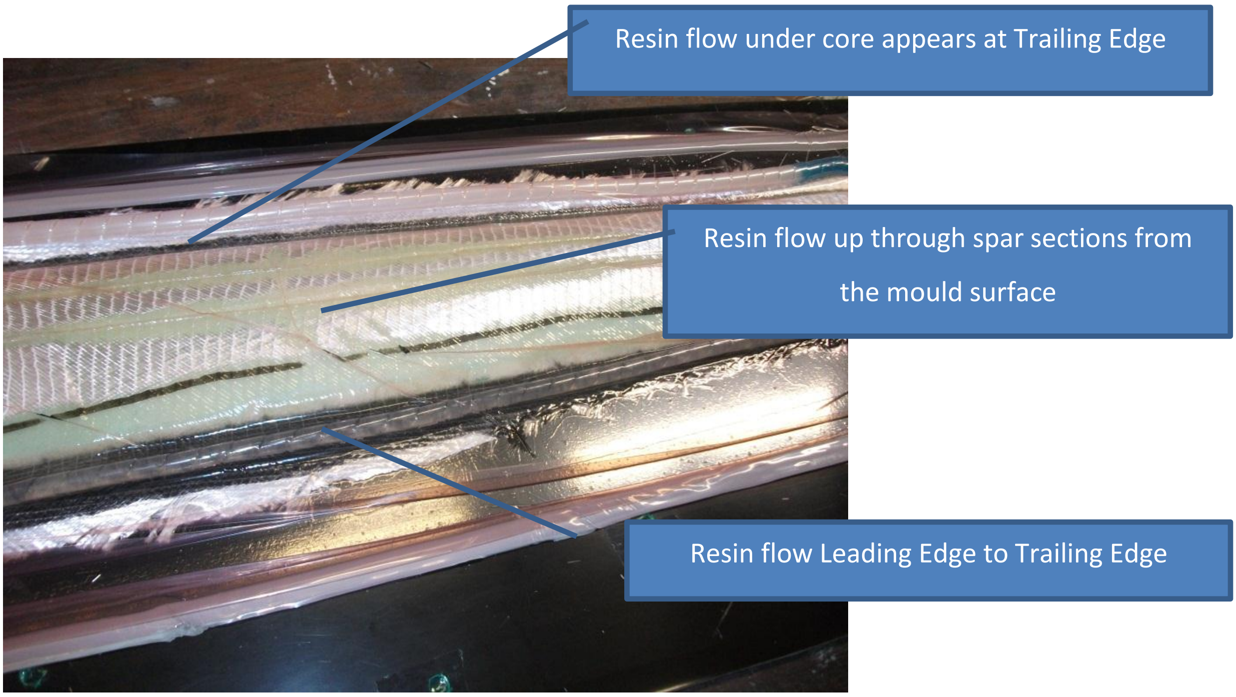


Figure 5.3 Half Mould Infusion Trial

Chapter 6 Discussion

Trials with various foam cores revealed a range of results. Figure 5.5.1 shows a cross section through an infused foam core sample. Reinforcement is correctly bonded to the foam core with no voids revealing a successful infusion.

6.1 Initial foam cores

Foam is closed cell so resin does not penetrate the foam. Resin starvation was evident on some samples particularly at the mould surface. Figures highlight such areas and thus highlighted an issue with foam cored infusions A similar problem occurred with foams designed for infusion with slots to act as resin channels. Figure 6.1 (a) foam-core infusion, (b) Resin starvation and (c) resin starvation on Rohacell-foam(b) shows areas starved of resin whilst the channels in the foam appear full of resin.

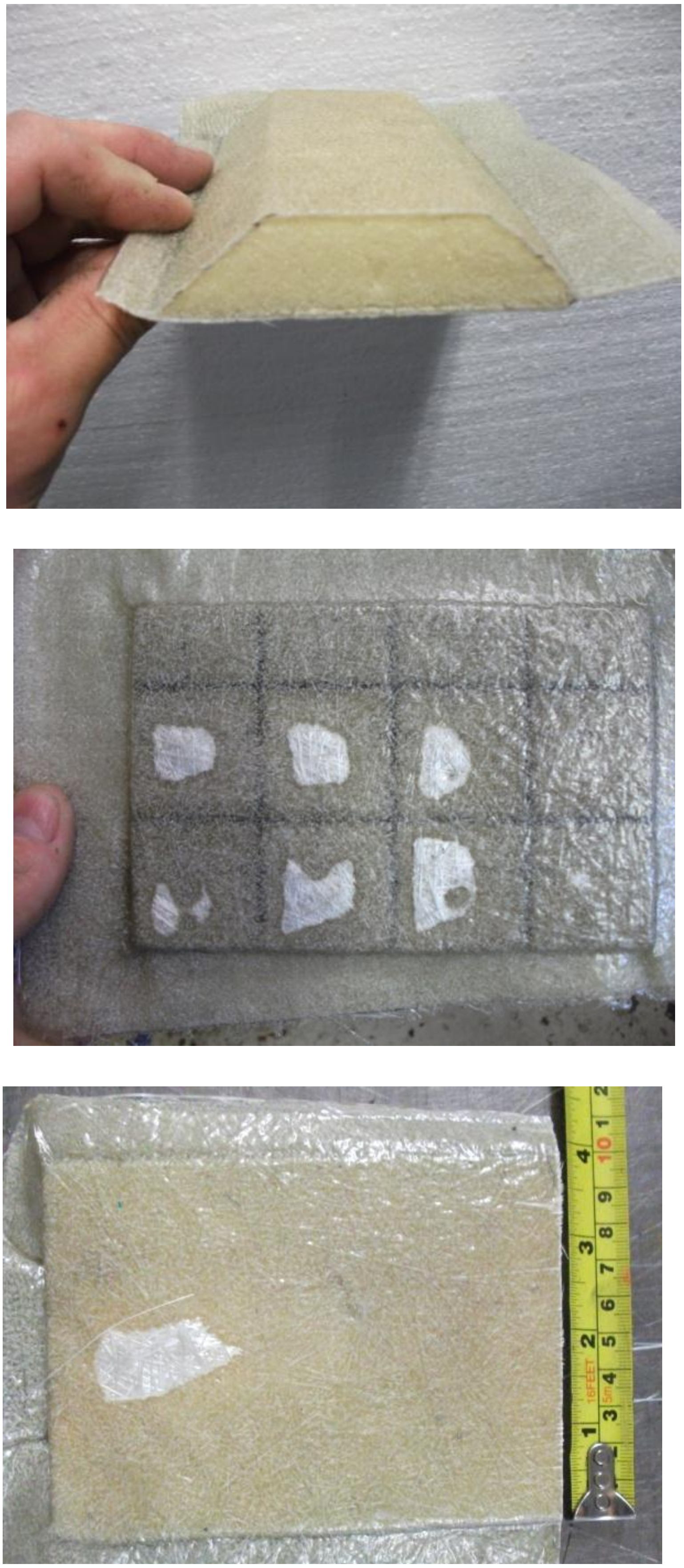


Figure 6.1 (a) foam-core infusion, (b) Resin starvation and (c) resin starvation on Rohacell-foam

Figure 6.2 show results of infusions on custom foam cores where holes and channeling were introduced. Various spacings shown in Table 5.3 show different foam thicknesses and hole spacings. Some samples conbined both hole spacings and custom channeling created at 0/90^{o} and 45/-45^{o} to determine any significant differences

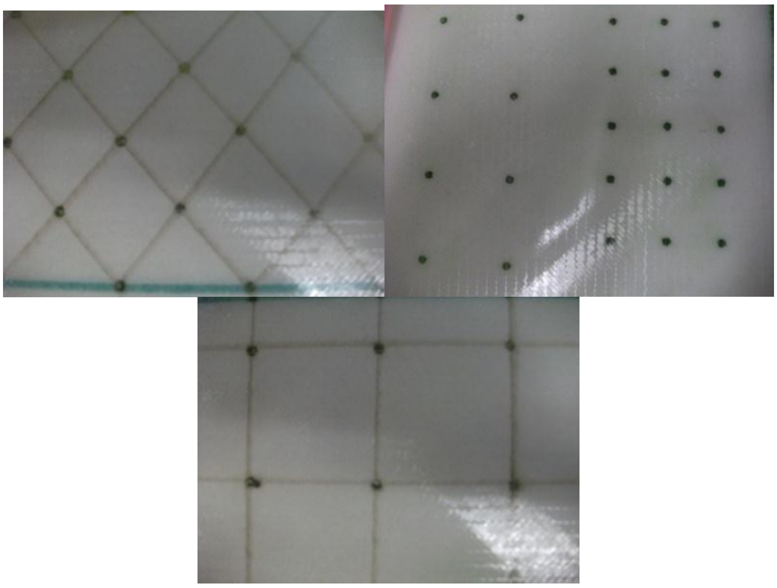


Figure 6.2 Foam core hole spacing and channelling

Figure 6.3 shows a foam core sample with holes during infusion, the view is from the mould surface. This clearly shows the infusion process as resin passed through holes in the foam. Each hole acts as a resin channel with resin eventally fully infusing the reinforcement. The top surface is already fully infused at this stage hence the distance between is lag between the flow front and the mould front.

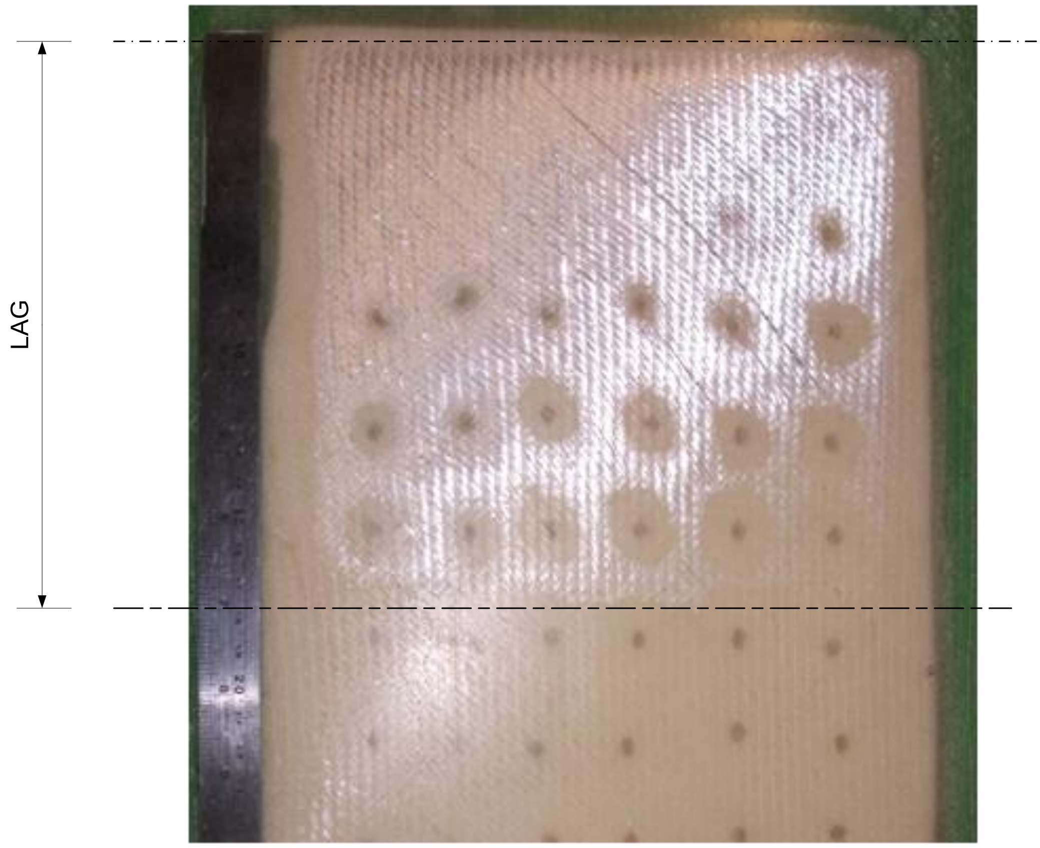


Figure 6.3 Flow Lag at mould surface

6.2 Custom Foam Core Results

Infusion across the flow media was consistent with previous benchmark tests with the foam seeming to have no apparent influence on the media, however flow at the mould surface was often hindered or produced resin starved areas or did not infuse. Poorly consolidated sharp corners or radii in the foam cross section acted as resin channels for resin to flow at a faster rate than over the infusion media surface and produced resin rich areas

Figure 6.4 reveals that holes through the foam core acted to allow resin flow down to the mould surface. Predictably the spacing of the holes had an influence on the flow front differential with finer spaced holes giving less lag between the flow across the surface of the media compared to the mould surface. Examination of foam cross sections revealed that sharp edges or corner radii could act as resin channels resulting in high resin content at these locations. Such features also acted as resin channels to promote faster infusion ahead of the main body of the sample. Figure 6.4 (c) highlights a resin rich region at the junction of two laminates

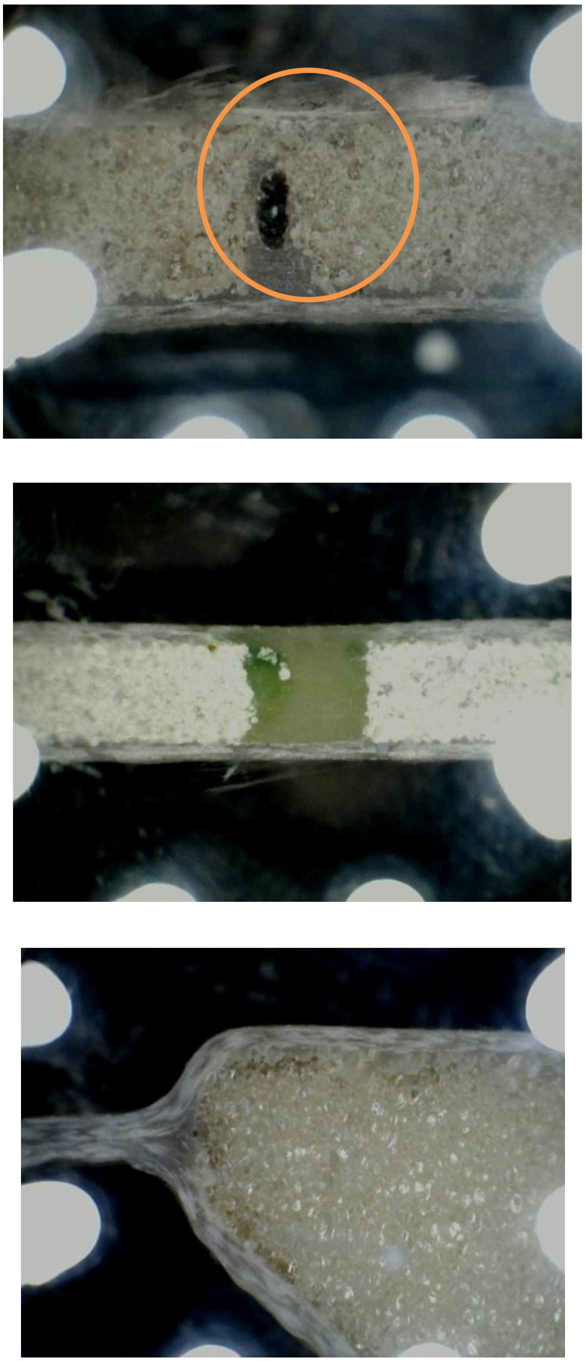


Figure 6.4 (a) Void inside Rohacell channel, (b) Section through resin feed hole and (c) Excess resin at ply intersection

Analysis of Rohacell foam samples revealed that deeper slots rather than shallow channels had carried resin but had the potential to create cavities within the laminate which could affect the structural performance of the composite. Examination of foam cross sections revealed that sharp edges or corner radii could act as resin channels resulting in high resin content at these locations. Such features also acted as resin channels to promote faster infusion ahead of the main body of the sample.

6.3 Foam Core and Spar Cap Trials

A stressed skin incorporating spar cap, foam core and multiple ply laminate structure was successfully infused. Holes in the foam core allowed transfer of resin to the mould surface and there was no evidence of voids or over saturation of the reinforcement materials. Microscopic observations showed infusion to be well consolidated with skin, core and spar cap fully infused and with no obvious voids or inclusions.

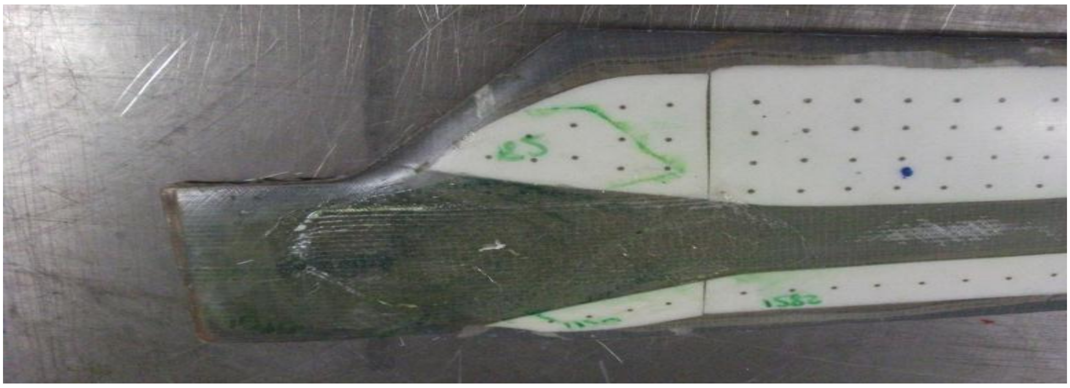


Figure 6.5 Stressed skin

Microscopic examination of the blade revealed correct consolidation of foam, spar cap and blade skins. Figure 6.6 shows each element of the blade fully infused with resin.

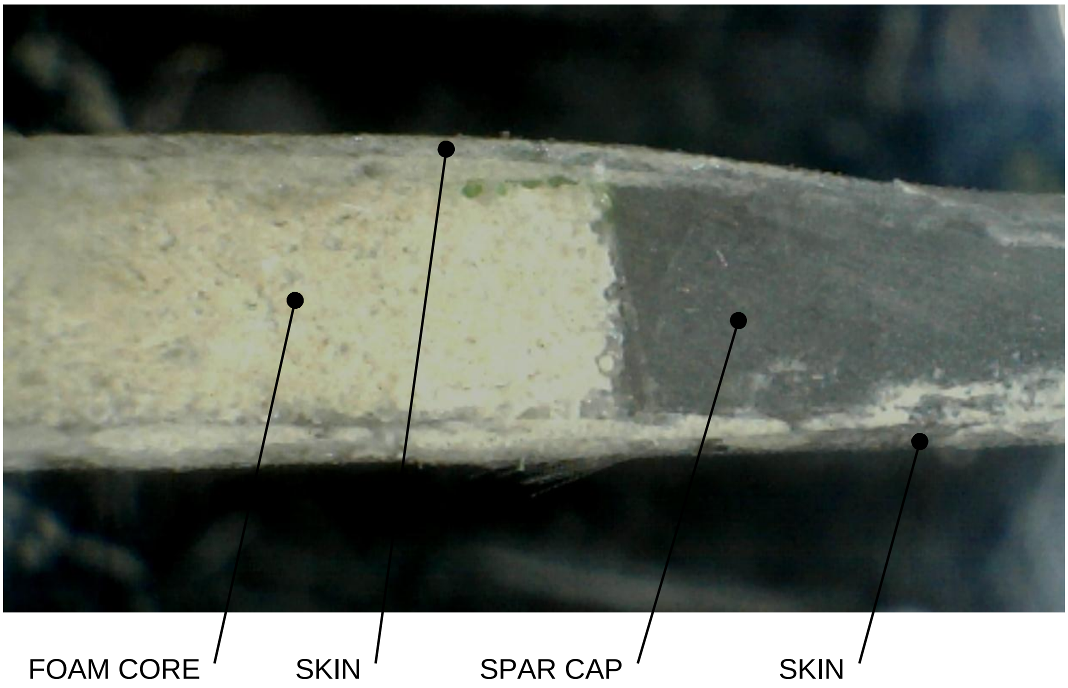


Figure 6.6 Microscopic Section through stressed skin

6.4 Custom resin channels

Results showed that infusion could successfully take place without the use of infusion media. Figure 7.2 shows resin flowing through the channels scored in the aero section foam

Figure 6.7 Resin flow through custom channels

6.4.1 Microscopic observations

Microscopic investigation revealed that resin had flowed through the resin channels with full consolidation of reinforcement to the foam. Figure 6.8 shows the resin channel full of resin whilst the reinforcement is well consolidated to the surface of the foam core

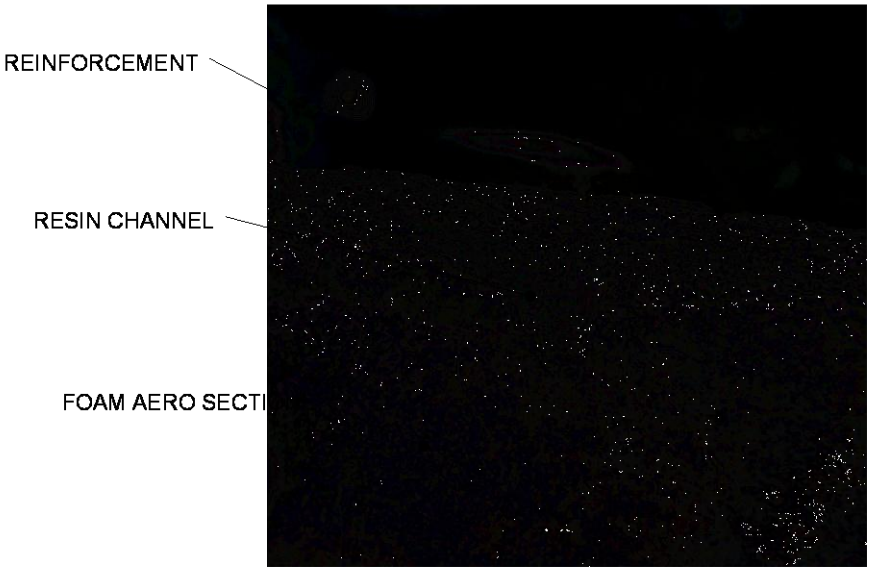


Figure 6.8 Section through resin channel in foam core

6.5 Affect of spar –caps

Observation of infusions did not differ from the custom channel trials with no direct way of observing flow through the spar section. Slicing of the section and microscopic analysis revealed successful infusion through the shear webs and through the spar cap region.

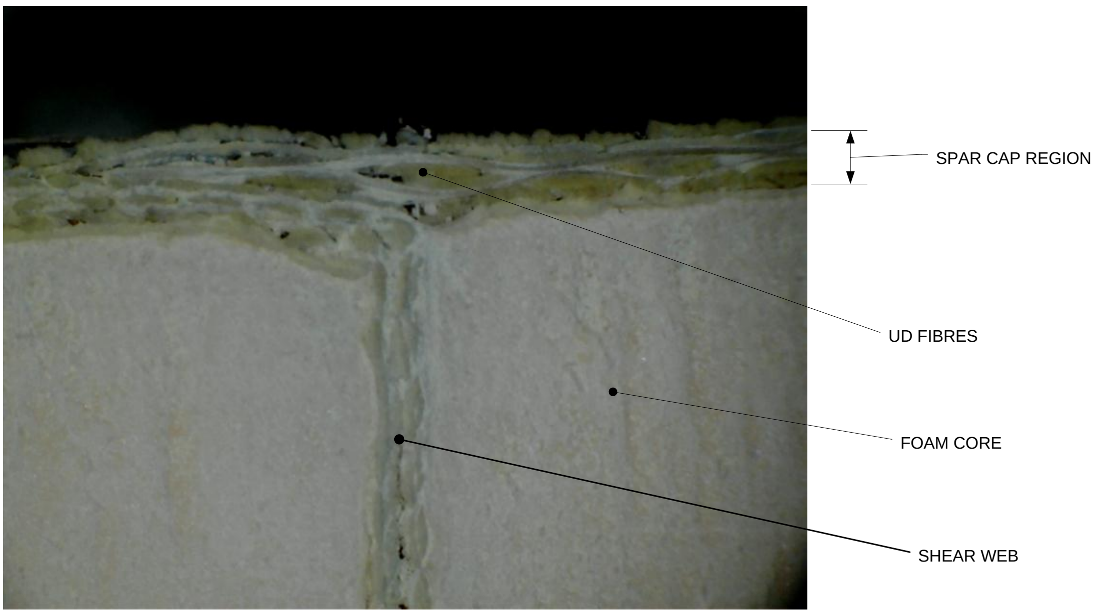


Figure 6.9 section through shear web

Results show the central spar section including the spar cap can be succesfully infused through the cross section of a blade. With single and multiple shear webs constructed in this manner it is then considered feasible for a whole blade to be infused in a single infusion with it's internal spar cap.

6.6 Full-core infustion

Tests confirmed the feasibility and repeatability of infusing 1m and 2.5m blades in a single process. The central spar structure was also successfully infused at the same time.

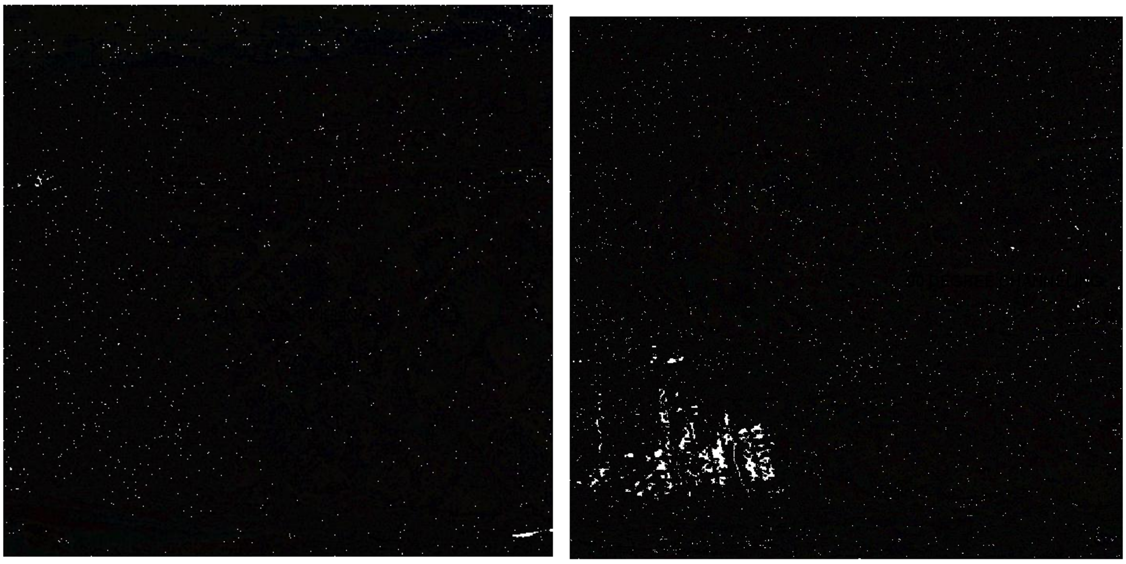


Figure 6.10 Spar infusion

Comparing linear channels to angled channels revealed the resin flow to be different in that flow through the linear channel progressed at a rate down the middle of the blade width whereas the angular channels encouraged a more even flow and infusion rate.

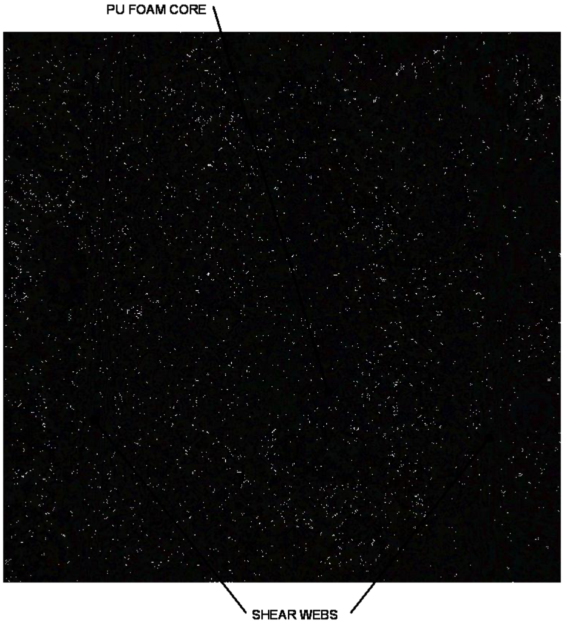


Figure 6.11 Section through shear web 1m PU core blade

6.7 Half mould infusion

Full infusion of 2.5m blades were successful and revealed infusion was successful at the mould surface. Custom channelling created on the mould surface revealed the resin had flowed at a faster rate at the mould surface and began to infuse up through the shear webs. This confirmed that resin was not only flowing at the mould surface but at a quicker rate than the non-channelled top surface and up through the shear webs. Clearly evident was flow up through the shear webs ahead of the resin flow at the leading edge which was the main inlet channel for the blade. This proved resin had flowed at the mould surface, along the custom channels and up through the section at a faster rate than the top of the blade which had no channelling.

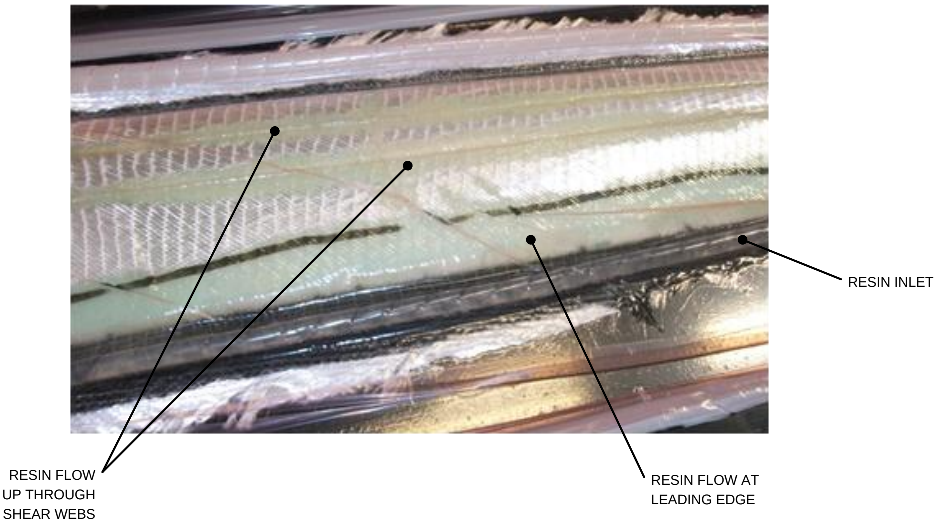


Figure 6.12 (a) Full infusion 2.5m blade and (b) Infusion through shear webs

Chapter 7 Conclusions & recommendations

The research aimed to develop an innovative manufacturing technology to allow the manufacture of a wind turbine blade incorporating internal structures as well as the outer skins of the blade in a single process. The process developed has met this aim and is transferable to any hollow composite product with internal structural members.

Current materials and manufacturing processes and in particular vacuum assisted resin infusion methods have been investigated allowing the manufacture of internal spars and supporting structures as an integral part of wind turbine blades.

The work completed has defined the nature of resin infusion across varying sections of both reinforcement material and sandwich core structures to determine a consistent and repeatable process.

7.1 Objectives met:

The objectives of the project were:

- *to develop innovative manufacturing methods for creating three-dimensional internal structures within composite components in one process*

The outcomes of the trials and subsequent manufacture of small wind turbine blades using the techniques developed have shown that three dimensional structures can be successfully produced within a vacuum infused product, the use of a custom foam core to channel and control resin flow through the laminate has allowed spar sections and other cross sectional detail to be manufactured.

- *to investigate and incorporate the use of vacuum assisted resin transfer techniques in the manufacture of internal structures*

Competence in the technique of resin infusion has been developed to a level where consistent and repeatable results have been achieved allowing the manufacture of small wind turbine blades. Understanding of the process and the various media used in the process resin has been developed. The use of the sandwich core material as the conduit for resin flow across the surface of the core but also through its cross section have been developed.

- *to investigate and utilise a range of core materials used in composites manufacture to improve stiffness, strength and fatigue in composite components*

Sandwich core materials were used in samples and in the finished blades, the creation of custom channels in the foam led to a series of tests to establish the nature of resin flow through these channels and how this could be utilised to better control resin transfer through the mould and laminate structure. Commercially available sandwich core materials were tested in their existing state and also customised to improve the flow of resin across and through them during infusion. Use of glass moulds and vacuum bag as a mould surface allowed the observation of flow at the mould surface

- *produce a composite component with internal structure comparable to current manufacturing methods targeted around small wind turbine blade manufacture*

Successful infusion of small wind turbine blades using the methods developed has shown that internal structures within a component can be achieved. Such cellular structures are often achieved with multiple part bonded components where the internal structure is manufactured as a separate component and blind bonded to the major external components. The process developed eliminates this need for secondary bonding.

7.2 Conclusions

The research has revealed that vacuum infusion technique, in its various forms, remains a dominant process for the manufacture of wind turbine blades and other sandwich cored composite products. Methods have been sought that improve the processes production time and quality by maintaining repeatability and consistency in the laminate structure

The apparently fickle nature of the process can be overcome with appropriate positioning of resin and vacuum points and an understanding of the nature of resin flow through the laminate.

The strengths of the study lay in the gradual development of the process and the satisfactory use of channels within a foam core to transfer resin under vacuum. This eliminated the use of flow media which was initially thought of as essential to the VI process

The practical nature of the experiments gave evidence of the nature of flow across and through a laminate and how this could be controlled and predicted.

The nature of flow through the laminate at a microscopic level remains unknown, whilst permeation of the laminate could be studied at the mould or vacuum bag surface the exact nature of the infusion was could be further developed

The implications of resin channels and resin shrinkage within the component could also be determined

The research was limited to small wind turbine blades and within the operational constraints of the composites laboratory available, whilst this gave opportunity and scope to experiment with various materials and resins to gain experience and competence in the process it did not fully explore the full range of materials available. The ability to control vacuum pressure was limited therefore all trials were conducted at the pumps capacity.

The wider aspects of the study could extend to the manufacture of similar hollow composite products which require an internal reinforcement structure, areas such as motorsport and aviation would benefit from development of the process. This may include the manufacture of wing sections and monocoque structures. The impact resistance of such structures could be explored.

7.3 Recommendations for further work

During the project several aspects have arisen which would benefit from further work and testing to better understand and improve the method:

7.3.1 Effect on polymer chain direction

Study on whether the direction of infusion has any effect on the resin and composite structure, does infusion in any particular direction give any benefits or limitations. Structural and microscopic analysis of samples created with a range of flow directions could be compared to establish if the direction of resin flow affects the direction of the polymer chain. If strength was discovered to be improved in particular directions or under certain laminate conditions then this could be exploited to optimise strength to weight performance.

7.3.2 Closed mould infusion

Infusion through a fully closed mould is the next obvious step in the creation of a full blade using this process. Creation of moulds to withstand vacuum and full length blade cores could be trialled with different flow channel configurations within the core.

7.3.3 Effect of custom channels in the RTM process

A study to see whether RTM or RTM Lite processes are influenced by custom irrigation channels in the way that has been shown in this research. Can the same ability to control the rate and direction of resin flow be exploited, similarly could custom foam cores within RTM manufactured components again complement and improve the process

7.3.4 Nature of custom channels under vacuum

Further tests could determine how the shape and dimension of custom flow channels influence resin flow. The depth of channels and the effect of shrinkage in these areas could influence the design process in establishing the optimum channelling to optimise resin flow without affecting the quality of the finished product.

7.3.5 3D core materials

Standard sheet foams exist with slotted channels e.g. Divinacell as does Lantor Soric® coremat material with structures that resist compaction under vacuum and allow resin to pass through a cellular structure in the material. Research could examine whether sheet materials with internal webs and structures could be developed. Research could expanded to see sheet materials containing longitudinal internal spars or a honeycomb structure which when infused would give a sandwich structure of two planar surfaces with a central stiff core to a range of sections.

7.3.6 Software simulation

The existence of software to simulate vacuum assisted manufacturing techniques e.g. RTM Worx® shows that a numerical solutions to predicting the nature of flow through a laminate is possible.

Whilst the software differentiates between flow of resin through irrigation channels and porous media (A. Koorevaar 2002). Channels within the custom core of a composite part could be explored further adding another element to the software to better predict resin flow and highlight the benefits of custom channels.

7.3.7 Alternative channeling media

The study has shown channels within foam core an effective conduit for resin transfer through a composite laminate, studies could extend to flexible core materials such as latex or silicone in the form of bladders with resin channels incorporated into the surface, once cured the flexible core could be removed with channels of resin remaining in the composite structure. The trials could extend to the use of soluble core materials giving the same channeling effect.

7.4 Future work - design for manufacture

Whilst the research aims did not extend to the design of a blade, a method of manufacture from design to finished product would be required to transfer the research findings to the manufacturing stage.

The design of a mould to facilitate the resin inlet and vacuum outlet from the mould would need to be considered as well as a method for sealing the mould during infusion. A mould for the production of foam cores would have to be created which could include the resin flow channels within the core. Dimensional allowances for laminate thickness would have to be addressed.

A specification would be required to develop suitable tooling and a typical laminate structure for the manufacture of a small wind turbine blade by resin infusion. To include:

- Resin Infusion of a full wind turbine blade and its internal structure in a single process
- Central spar and shear webs to be created within the process
- Spar cap to be included along the length of the blade

- Root section to include location for inserts for root attachment
- Multiple laminates of reinforcement along the length of the blade
- UD fibres along leading and trailing edges
- Mould edge to be sealed by vacuum and not clamped
- Moulds to be reinforced to prevent deflection or deformation naturally or under vacuum

7.4.1 Plug/buck Manufacture

3D CAD modelling of a blade design would give the opportunity to manufacture plugs by CNC routing. Appropriate finishing of the plugs would allow the manufacture of mould tools. Whilst the dimensional accuracy of the plugs can be accurately controlled the structural integrity of the finished plugs are likely to be an area for concern therefore a stable material such as epoxy board or a metallic plug would be required. Similarly a metallic mould could be manufactured from the same CAD data.

7.4.2 Inlet/Outlet ports

To facilitate resin infusion the mould would be created with ports for resin inlet and vacuum connection. To assist sealing of the mould prior to infusion a double vacuum seal would be incorporated, eliminating the risk of air leakage into the closed mould. This would allow the mould to be sealed by a separate vacuum supply prior to infusion.

7.4.3 Mould features to assist VI process

The mould would be created with the split line along leading and trailing edges and hinged to ensure correct alignment between mould halves. Mould halves would be reinforced with an external structure to maintain dimensional accuracy and prevent deformation along the contour and length of the blade. The strength of the supporting structure should not allow the mould to deflect under vacuum

7.4.4 Blade core mould

The moulds for production of the blade cores should reflect the shape of the core allowing for the laminate thickness along the length of the blade. Laminate thickness would be replicated with the use of calibrated wax sheets within the blade mould, this approach gives flexibility in the process if the laminate structure was to alter as the blade design was refined. With fabric compressibility an important factor, accuracy in the foam core mould would serve to maintain consistency.

The pattern of flow channels would be incorporated as raised profiles on the mould to give finished flow channels on the core. Removable sections to establish the shear web thickness would be created so casting of a core would produce three sections. Flexible silicone cores could also be created in a similar fashion and cast within the mould. Soluble cores could also be cast in the same mould.

7.4.5 Inlet and outlet positioning

Points for resin inlet and vacuum outlet would need to be established with capacity in the mould design to allow placement changes. Channels in the mould perimeter could serve as either resin inlet or vacuum tracts

7.4.6 Post-curing

If the resin type requires post cure this may be facilitated into the mould rather than relying on a large oven, post cure up to 80 degrees is achievable with the inclusion of a hot water jacket or water rail system attached to the exterior of the mould

7.4.7 Conclusion

This work set out to explore the vacuum infusion process and develop a technique for creating internal structures within a part. This has been achieved and has led to competence and understanding of the process and beyond.

It has raised further questions into this method of composite manufacture which could influence designers to work with this method of manufacture in mind. It is hoped such engineers can benefit from this work and adapt it to suit their own application.

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