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THE FUTURE OF COMPOSITES FOR MARINE APPLICATIONS

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ABSTRACT

Composites are commonly applied in the marine industry due to their high strength-to-weight ratio, improved corrosion resistance, and ability to be moulded into continuous complex geometries. However, some industries have been slow to adopt these new materials due to numerous technical and commercial challenges. This thesis presents a comprehensive investigation into the most critical challenges currently preventing more widespread use of composites in the marine industry.

Typical marine structures are designed to withstand harsh environmental conditions at sea over a 30-year service life. It is crucial to understand the long-term change in material properties due to exposure in this environment. However, it can be difficult to theoretically predict these changes as they are dependent on multiple factors, including the production process, manufacturing variations, environmental conditions, and selected constituent materials. Accelerated conditioning experiments are typically conducted on representative laminates to simulate exposure to harsh conditions over the service life. These tests can be time consuming and costly, so investigations have been conducted by the author to investigate the viability of further accelerating the conditioning process on a range of marine composite laminates. The results indicate that further acceleration leads to, on average, greater knockdowns in laminate strength. The investigation also found a significant variation in seawater degradation amongst a range of marine composite laminates, highlighting the importance of durability testing. The selection of “standardised laminates” is suggested as a means of focusing global research in this area, thus improving long-term durability predictions, and increasing confidence in large marine composite structures. A potential trend between laminate moisture uptake at saturation and strength degradation was also identified which could be used with numerical predictive tools to further simplify initial material down-selection in industry.

A lack of affordable and robust manufacturing processes was identified as a key limitation currently preventing the use of composites in primary structures of large (50m+) commercial vessels. To address this, a rapid manufacturing process development approach is proposed based upon experimental trials and expert industry knowledge. Using this approach, a manufacturing process has been developed for a 75m hull shell and validated via the production of a full-scale demonstrator section. Vacuum assisted resin infusion was selected as the most appropriate production method for this case study as it enables large composite structures of sufficient quality to be manufactured in a relatively affordable manner. Glass fibres and toughened vinyl ester resin were used to manufacture this structure. The greatest challenge of this work was achieving a one-shot 6m vertical infusion with approximately 1 tonne of resin. A full-scale demonstrator was successfully produced; however, the financial risks associated with applying this infusion procedure to a 75m hull cannot be ignored. Whilst the infusion process can tolerate changes in ambient temperature and layup tolerances, the use of a vacuum bag at this scale leaves this process highly susceptible to air leaks. Therefore, whilst the process is technically viable, further improvements should be made to improve commercial viability.

Commercially available automated manufacturing technologies are investigated to reduce process risk and production costs of the selected case studies. Automated production line concepts are proposed, including the automated modular construction of a hull shell assembly using pre-infused panels. This work acts as a first step towards automating the production of large composite hulls and tidal turbine blades, highlighting the key challenges and areas of future development. Further work is required to conduct further structural design iterations, develop a robust panel assembly procedure, and integrate individual automated manufacturing solutions into a complete production line.

The proposed durability prediction and rapid infusion development methodologies, procedures for manufacturing large composite structures, and automated production line concepts presented in this thesis provide the marine industry with tools to support the implementation of composite materials across a wider range of applications in a more cost-effective and lower risk manner.

DEDICATION

This thesis is dedicated to all those who seek to improve the safety and sustainability of marine structures across the globe through the use of advanced lightweight composite materials.

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AUTHOR'S DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: OLIVER PARKS DATE: 16/06/2020

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1 FUTURE CHALLENGES AND OPPORTUNITES FOR MARINE APPLICATIONS OF COMPOSITE MATERIALS

1.1 Introduction

The marine industry consists of four key markets: Commercial, leisure and naval vessels, and renewable energy. The construction and operation of seafaring vessels have existed in various forms throughout recorded human history and represent the largest markets within the marine industry. The materials and processes used to construct seafaring vessels have evolved over time, with wooden ships being the primary method of nautical transport for thousands of years until the development of advanced steel assemblies in the 19th century. Materials and processes continue to evolve to this day, with conventional steels being replaced by more advanced composite materials across many industries in the past decades. This has been attributed to general improvements in resin and fibre performance, a greater understanding of composite laminate behaviour, improvements in manufacturing capabilities, and the emergence of new commercial applications.

Fibre reinforced polymer matrix composite materials provide many advantages over steels in marine applications. Their higher strength-to-weight ratio allows for lighter, more structurally efficient designs, providing multiple benefits such as reduced fuel consumption, operational costs, and improved manoeuvrability of seafaring vessels. Unlike conventional steels, composites are not prone to corrosion, leading to fewer maintenance intervals and further reduced operational costs. Manufacturing processes utilising composite materials can create continuous single-part structures with complex geometries and are therefore ideally suited for watertight hydrodynamic structures such as boat hulls and renewable energy devices. Composite materials constructed from glass or carbon fibres with either epoxy, vinyl ester or polyester resins are most commonly used in the marine industry due to a combination of cost, mechanical properties and long-term durability. These materials are typically used to construct recreational vessels such as pleasure craft/yachts, racing vessels and fishing boats. Composite materials have also been used to manufacture military vessels, with the additional advantage of non-magnetic hulls proving to be extremely beneficial for minehunters such as the H.M.S. Wilton and H.M.S. Sandown (Thomas, 1972) (Mouritz, A.P., et al., 2001). The commercial shipping industry has yet to fully embrace this new technology due to several concerns related to the cost, design, manufacture, and long-term operation of such large composite structures. Nevertheless, current trends indicate that the use of composite materials in critical marine structures will continue to expand, in many cases replacing steels as key structural materials. For example, the European network for Lightweight Applications at Sea (E-LASS) is leading research in light-weighting commercial ship structures using composites and other advanced materials (E-LASS, 2020).

The development of composite materials has also resulted in the emergence of new commercial applications within the marine industry. Renewable energy technologies such as offshore wind, wave, and tidal stream turbines require strong, lightweight, and durable materials to be formed into complex and continuous geometries in order to be commercially viable. Wind turbine technology has evolved significantly over the past decades thanks to high levels of financial investment, resulting in a large industry of manufacturing and operating turbines both onshore and offshore. Wind turbine blades of up to 107m in length have been produced using composite materials (LM Wind Power, 2019). Wave and tidal energy devices on the other hand have not achieved the same level of technical maturity and still require significant levels of technical and commercial development.

The advantages of using composite materials in marine applications are clearly apparent. The evolution of composite materials and manufacturing processes in recent years has created an opportunity to further develop existing products whilst also enabling the creation of completely new technologies and markets. However, the adoption of composite materials within certain markets, such as the commercial transportation and shipping industries, has been slow, indicating the presence of technical and commercial barriers. Further analysis of the marine market and identification of these barriers are the first steps towards the wider implementation of composite materials within the marine industry.

1.2 Marine Market Analysis

It is important to understand how the global markets within the marine industry are evolving so that research can be focused towards areas of greatest importance, enabling UK marine industries to further develop their technical capabilities and experience further growth in the coming decades. Three publicly available reports are referred to in this section that identify the most lucrative commercial opportunities and the technical advancements required to fully exploit the advantages of composite materials in these applications.

Global Marine Trends 2030 outlines the key drivers that will influence global marine industries between 2010 and 2030 (Qinetiq; Lloyd's Register; University of Strathclyde, 2013). Significant population and economy growth are predicted across the globe, with global GDP rising by 300% and the global population reaching 8 billion people. This growth is expected to result in a 40% increase in global energy demand by 2030, creating an increased demand for natural resources such as oil and gas. As 90% of international trade is facilitated by seafaring vessels, this demand will lead to a significant expansion in seaborne trade, and thus the shipbuilding market.

Greater energy demands will also lead to growth in offshore energy supply such as oil, gas, and renewable technologies. Whilst oil and gas demands are expected to rise by 2030, offshore wind is predicted to see the most accelerated growth compared to 2010 levels, with more than 65,000 installed devices worldwide by 2030. This is primarily due to the increased focus on climate change and the greater level of technical advancement compared to other offshore marine technologies. Less growth is expected for wave and tidal current energy, with 22,000 and 50 installed devices predicted by 2030, respectively (Qinetiq; Lloyd's Register; University of Strathclyde, 2013).

It is apparent that significant growth is predicted across the global marine industries. Technical advancements in the manufacture and operation of vessels and renewable energy devices will be required to meet future global demands. The UK Marine Industries Technology Roadmap identifies several priority opportunities and technical capabilities that are required to meet these demands (IfM Education and Consultancy Services Limited, 2015). The report recommends an "extended use of composites and other novel materials" to produce more durable, lightweight structures. To achieve this goal, several technical capabilities must be developed by 2030. Manufacturing larger composite structures of 50m and 100m in length are identified as key technical capabilities for the short term (2015/2016) and long term (2020/2030) respectively, with larger composite hulls being mentioned specifically. Advancements in manufacturing processes are also required, such as automated manufacture, affordable major vessel structure, 3d printing, modular structures, adaptive moulds, integration of design and build, and improved build quality. The adoption of composite materials in these structures will also lead to new challenges that must be overcome. Recycling/end-of-life options and meeting international fire safety regulations are identified as important challenges.

Global Marine Technology Trends 2030 also features advanced materials such as composites as one of eight key transformational ocean space technologies (Lloyd's Register; Qinetiq; University of Southampton, 2015). The report also highlights the uncertainty around implementing these materials within existing markets, as current regulations will need to be modified and amended to accommodate these new materials. The key drivers for composites in the marine industry are identified as operational cost, safety, and durability. A separate market review conducted by the author consisting of various feasibility studies for a range of composite marine products produced similar findings to these reports (Parks, 2016).

1.3 Selection of Suitable Case Studies

Large vessels and offshore renewable energy devices appear to be the most lucrative commercial markets for composite materials. However, there are several technical limitations that currently prevent the widespread use of these materials within these markets. The research in this thesis aims to address these limitations. To do this, the work will be focused around two specific case studies that represent shipping and offshore renewable applications.

In the shipping and marine transport industries numerous smaller ship components are currently manufactured from composite materials, such as hatch covers, railings and mast supports. This is primarily due to the lower weight and enhanced durability of composite materials. However, despite the advantages of composite materials, primary vessel structures, such as superstructures and hulls, are currently manufactured from steels.

Superstructures are situated above the main deck. Reducing the weight of these structures by implementing composite materials would not only reduce fuel consumption, but also lower the vessel's centre of gravity, increasing stability and/or total load capacity. For this reason, composite superstructures are of great commercial interest. However, large commercial superstructures are currently manufactured from steels due to concerns around fire safety and the lack of affordable and robust composite manufacturing techniques at this scale.

The hull consists of internal decks, bulkheads, and a continuous outer shell, the latter of which is exposed to harsh marine environments, including sea water and salt spray at varying temperatures. Composites appear to be well suited for this application due to their greater long-term durability and ability to be shaped into continuous, complex hydrodynamic geometries, enabling fewer maintenance intervals and lower operational costs. Lightweight composite hulls, in combination with composite superstructures, can also provide reduced fuel consumption through lower overall structural weight. As with superstructures, the lack of affordable and robust composite manufacturing techniques is a key limitation. Furthermore, the long-term degradation of composite materials in marine environments is difficult to accurately predict, leading to uncertainties in structural designs. The novel design and manufacturing challenges associated with applying composites to large ship structures, combined with high development costs, leads to considerable financial risk. For example, the cost to design and build a 104m steel patrol vessel (HMCS Harry DeWolf-class) was CA$3.5 billion (Government of Canada, 2015). Implementing novel composite materials is expected to significantly increase this cost.

The issue of predicting long-term composite material degradation is also highly relevant to renewable energy devices, where structures must continuously operate in harsh marine environments for up to 30 years. Composites are primarily used in these applications to manufacture turbine blades, as their high strength-to-weight ratio and improved durability allow for more efficient and robust turbine designs. These applications can be split into two categories: above water and submerged.

Wind turbine blades are the most common above-water application of composite materials in the renewable energy industry. Wind turbine blade manufacture is an established industry with affordable and robust manufacturing processes. However, leading edge erosion is currently a major challenge for existing devices due to high blade tip speeds and the presence of particulates, salt, and raindrops in offshore environments.

Submerged technologies such as tidal and wave energy devices must be designed to withstand long-term material degradation due to moisture absorption into the composite structure. Difficulties in accurately predicting this long-term degradation can lead to over-engineered designs and uncertainties over necessary maintenance intervals. This is not a critical concern for wave energy devices as they typically operate on the sea water surface, and thus can be easily accessed and inspected. However, tidal turbines must be installed deep beneath the surface (20-40m) to extract energy more efficiently from tidal currents. As a result, these devices cannot be easily accessed, and so reducing maintenance becomes a higher priority.

The greatest challenge facing tidal turbines is financial risk, resulting from high installation costs and uncertainties around long-term performance. For example, the OpenHydro tidal turbine's development cost exceeded €90 million, with a decommissioning cost for one turbine estimated to be $4.5 million (The Times, 2017) (Global News, 2020). Development costs are high because these novel devices must be designed to withstand the high loads generated by tidal currents whilst being permanently fixed to the seabed and submerged in seawater for up to 30 years. Tidal turbine design specifications demand large, thick composite structures which can be difficult and expensive to manufacture. Instillation of the turbine and supporting cable infrastructure is also extremely challenging and costly due to the strong tidal currents and is typically limited to short windows during the day when tidal currents are less intense. The installation procedure also requires specialist high-load capacity vessels, underwater equipment, and trained diving teams. These may also be required during every maintenance interval, leading to potentially high operational costs. Uncertainties around long-term material degradation and structural performance, and the lack of pre-existing 30-year-old case studies create the potential for unplanned maintenance, and thus considerable financial risk.

Tidal turbines are also limited to a few select locations around the globe where tidal currents are strong enough to justify installation, whereas wind and wave devices can be installed in a wide variety of locations. High financial risk, limited installation sites and a lack of convergence towards a single unified turbine design explains why growth in the tidal turbine market is predicted to be much lower than for other offshore renewable energies. Even so, tidal turbine designs continue to be developed around the world because unlike other renewable energy sources, tidal flows are predictable and enable the regular and reliable generation of electricity all year round. Addressing the high development and manufacturing costs of this technology and the uncertainties around long-term material degradation and device maintenance and will reduce financial risk, and thus enable tidal turbine technology to be more widely adopted around the globe.

Large commercial hulls and tidal turbine blades are selected as the two applications for further investigated in this thesis. A 6m long, 2m wide, 200mm thick monolithic tidal turbine blade and a 75m long, 6m high, 280mm thick (sandwich and monolithic construction) fully composite hull shell are selected as the specific case studies for this thesis. The tidal turbine blade features complex double curvatures and is constructed from glass fibre and epoxy resin. The hull shell is predominantly a single curvature structure with local double curvature regions at the bow and stern.

Together these applications cover the main technical challenges for applying composites in large marine structures, whilst also representing two very different industries. Both applications share technical challenges related to moisture degradation and long-term durability; however, ship structures have unique manufacturing challenges due to their very large size whereas tidal energy structures have the most demanding strength and stiffness requirements due to the high loads exerted on the blades. These challenges are explored in further detail in the next section.

1.4 Current Challenges and Limitations for Composites in Marine Applications

Composite materials are a relatively new technology compared to more conventional construction materials such as wood and steel. Whilst composites offer many advantages in marine applications, they also pose new challenges that must be overcome. This section explores the key challenges and limitations that prevent the widespread use of composite materials in large ship hulls and tidal turbine blades. The purpose of this section is to identify the most critical challenges where research should be primarily focused.

1.4.1 Manufacturing Capabilities

The manufacture of large steel structures is well established, having been developed and refined over centuries. Standard grades of metal alloys can be defined and manufactured on large scales for a range of markets, resulting in widely available and affordable range of materials. Extensive testing and evaluation of these isometric materials over the years has enabled the generation of standardised material databases and design regulations for a variety of applications. Standardised manufacturing and assembly techniques combined with standard material grades has resulted in streamlined design and manufacturing procedures for metallic structures, which in turn reduces manufacturing duration and cost.

Composites offer many advantages over steels, however the design and manufacturing processes used to create these structures are more complex. This is a major limitation of composite structures, and the development and production costs must be factored into a life cycle assessment for each application to determine whether the operational advantages outweigh the disadvantages of a more complex design and manufacturing process. Composite manufacturing processes tend to be manually intensive, having evolved over the years into a trade skill rather than a set of standardised procedures. These processes are typically conducted in controlled environments, or clean rooms, as variations in process parameters, such as temperature or humidity, can have a detrimental effect on the materials, process, and final product. Successfully manufacturing composite products therefore requires skilled production staff who understand how to handle and process these materials. "Standardised procedures" are typically developed internally within each company based upon a comprehensive understanding of the design requirements, materials, and processes.

The size and geometry of the selected case studies add an additional level of complexity to the manufacturing process, especially in the case of large (50m+) composite hulls which are typically larger than most clean room environments. For greater cost-effectiveness and minimal disruption to existing shipyards, it is proposed that the transition from steel to composite be achieved by adapting the manufacturing process to the shipyard environment. Shipyards are located alongside large bodies of water, and thus can experience high winds and significant levels of sea spray and humidity. The construction of ships is conducted within large open workspaces within hangars, in which a number of different steelwork tasks are conducted, including material storage, cutting, drilling, welding, sub-structure assembly and final assembly. Multiple manufacturing projects may be conducted within the same workspace, and the large hangar doors may be open for extended durations to enable movement of materials and structures, exposing internal areas to potentially high levels of wind and humidity. These factors create a relatively uncontrolled environment which shall be referred to throughout this thesis as a "shipyard environment". This information on shipyard practices was gathered by the author during visits to shipyards as part of the RAMSSES project (further details available in later sections).

In addition to the challenge of adapting the manufacturing process in relation to the environmental factors discussed above, shipyard workers must also be trained to handle and process composite materials. Composite materials, unlike steels, tend to have more restrictive storage requirements, resulting in the need for dedicated material storage facilities. For example, pre-impregnated (prepreg) materials should be stored in air-tight refrigerated containers to preserve shelf-life, with stringent material traceability documentation used to monitor the total time each material spends outside the refrigeration unit. Other chemical substances such as laminating and infusion resins, accelerating agents and mould preparation and cleaning chemicals must be stored in dedicated fire-proof cabinets within a specific temperature range as stated on the substance's safety data sheet (typically between 5°C and 35°C). Personal protective equipment (PPE) such as nitrile gloves, air filtration face masks and full-body overalls should be worn to protect the workforce from breathing harmful fumes and making skin contact with harsh chemical substances and irritable stray fibres, whilst also limiting contamination into the composite materials during handling and manufacture. The issue of PPE does not seem to be a significant barrier as there is already a culture of wearing PPE in shipyards for various metalworking tasks (such as welding masks, gloves, and overalls). Shipyard workers will also need to be taught how to implement the relevant composite manufacturing procedures (the most relevant of which are discussed below). These skills include mould and material preparation, applying vacuum bags and other consumable products, ply layup, draping and handling, and executing resin impregnation procedures such as contact moulding, resin infusion and resin transfer moulding (RTM). These trade skills must be taught and refined over years of experience and are all crucial for ensuring a sufficient level of quality in the final manufactured part. Developing a composites manufacturing capability within a steel shipyard could therefore require significant time and cost investments. This information relating to composites manufacturing processes was obtained by the author throughout several years of working with industry experts at Airborne UK, during which time several commercial marine composite products were successfully manufactured.

There is a wide range of composite manufacturing processes that can be used to create marine structures. A process is typically selected that meets the specific requirements of the application, including size, geometry, cost, and structural/quality requirements. The most common processes used to manufacture a range of marine structures feature the manual layup of either dry or pre-impregnated (prepreg) reinforcement materials onto a tool surface to create the desired geometry. Four options for adding liquid resin and/or processing these materials are identified based upon the relative weighting of these requirements.

1.4.1.1 Contact moulding and spray-up

Contact moulding or spray-up processes can be used for a wide range of products with less stringent structural requirements. In these processes the dry reinforcement and liquid resin are applied to the tool by hand. In contact moulding the resin is applied to the dry reinforcement using a brush, whilst spray-up utilises a spray gun to simultaneously deliver short fibres (10-40mm) and resin onto the tool (Astrom, 1997). These processes do not typically feature vacuum consolidation or heated cure and are susceptible to contamination and defects. Laminates produced with these methods typically feature lower fibre volume fractions and structural properties compared to more advanced techniques, however these processes are simple, versatile, and have low setup and operational costs. With a skilled workforce and robust manufacturing procedures, it is possible to create sufficiently strong and durable products for a range of composite products of varying geometric complexity and size. The manufacture of boat hulls is one example of where these processes are commonly used. Ranger boats use hand lamination and spray-up techniques to manufacture fibreglass fishing boats (Ranger Boats, 2018), whilst Dufour manufacture a range of yacht hulls up to 18m in length using these techniques (Cruising World, 2016) (Dufour, 2020).

1.4.1.2 Vacuum assisted resin infusion

Vacuum assisted resin Infusion (VARI) is generally used to create medium (1-5m) to large (5-50m) composite structures with higher fibre volume fractions and structural properties than contact moulding or spray-up. A vacuum bag is applied over the tool which allows resin to be drawn through the dry reinforcement via vacuum suction. Room temperature curing resins can be used to minimise heating requirements, and thus reduce processing costs. The infusion process can be relatively complex compared to other process options and can therefore require significant development time and cost. VARI provides a good compromise between production cost, structural properties and process versatility and is best suited to the continuous production of large, high quality, bespoke products such as yacht hulls. Princess Yachts produce composite yacht hulls of up to 40m in length using resin infusion (Charter World, 2011). Sunseeker also infuse composite hulls of up to 40m in length for their range of luxury yachts (Luxury News Online, 2016) (Sunseeker, 2020). Another yacht manufacturer, Oyster Yachts, use a 40m oven to post-cure their 37m long infused hulls (Super Yacht World, 2010) (Oyster Yachts, 2020). These companies are just three examples of UK-based large composite yacht manufacturers. Whilst the UK is a world leader in this market, it is apparent that infusing hulls up to 40m in length is a well-established process.

Current yacht composite hulls are typically constructed as continuous sandwich panels that are 20-100mm in total thickness and 3m in height, whereas 50m+ hulls have maximum thicknesses of ~300mm and may consists of both monolithic and sandwich sections, with a maximum height of 6m (See case study in Section 3.2). Infusing higher sections results in greater hydrostatic pressures, which negatively impact the infusion process and hence increase process complexity. Greater sectional thicknesses also significantly increase the complexity of the infusion process. Depending upon the infusion configuration and setup, thin laminates may be treated as 2D in-plane infusions as the resin flow in the through-thickness direction is relatively insignificant compared to the length and width of the structure. This is an important assumption, as it typically allows the placement of resin inlets on the easily accessible vacuum bag surface, simplifying the production process. This assumption is not valid for thicker sandwich panels where through-thickness resin flows may be more significant.

Ned Popham, from Sunseeker Poole, provides a comprehensive overview of the resin infusion process as applied to the manufacture of large marine parts such as yacht hulls (Popham, 2019). This overview outlines the complexities of a large-scale infusion process, including material selection and characterisation, process setup, resin flow behaviour, exotherm, shrinkage, tool design, necessary plant equipment and measurement of relevant process variables. Resin flow is determined by the preform permeabilities and cross-sectional area, resin viscosity, infusion distance, and the applied pressure differential. These are all variables that can change from one infusion to another due to variations in material batches, ambient environment, and material handling/layup. The infusion process can therefore be sensitive to unintended variations in parameters such as temperature changes or layup inconsistencies caused by human error. Popham provides examples of resin race tracking occurring due to gaps in or around the preform or incorrect positioning of infusion consumables. Race tracking is a phenomenon where resin races along unintended paths causing the formation of dry regions, or lock-offs, that are separated from the vacuum outlet, resulting in local decelerated or stationary resin flows and potentially large defects within the product. Popham also outlines the importance of process setup and consumables positioning when dealing with 3D resin flows, as these can be significantly more complex and prone to issues.

Whilst there are no commercial examples of resin infusion being used to manufacture composite hulls larger than 50m, it has been reported that SNSZ, a Russian shipyard, has successfully infused an 8.5m tall hull demonstrator as part of an investigation into the production of a 62m minesweeper (Composites World, 2014). There are very few details of how this process was conducted or the quality of the final part, although it is reported that the infusion was conducted in two stages to overcome hydrostatic pressures and therefore successfully raise the resin up to 8.5m in height. The shipyard has recently invested in dedicated fibreglass production facilities as their historical expertise primarily lies in manufacturing large steel vessels (PortNews, 2013) (Nevsky Shipyard, 2020). Whilst the 8.5m demonstrator infusion is a significant achievement, the shipyard does not appear to currently produce composite vessels of this size, with their most recent composite vessel being a 26m passenger catamaran (Ship Technology, 2017) (PortNews, 2016). This indicates that the process requires further development, or there are other challenges such as cost, long-term durability or design regulations that are preventing the use of composites in larger vessels. Either way, it is not yet clear whether the infusion process can be applied to manufacture large vessels, so further research is required to understand the specific challenges and limitations in greater detail.

Wind turbine blades are also commonly manufactured using VARI due to their size. Blades of up to 107m have been infused, typically in halves (split along the aerofoil chord line) and later bonded together in a closed, controlled environment (LM Wind Power, 2019). Wind turbine blades are long and slender structures with monolithic wall thicknesses of up to 150mm and total sectional thicknesses of up to 4m at the blade root (R.P.L. Nijssen, 2013) (Composites World, 2019). As these blades are infused in halves, the effective maximum infusion height is approximately 2m. Therefore, whilst wind turbine blades share some similarities with the selected case studies (wind blades and hull are a similar length whilst tidal and wind turbine blades share similar geometry profiles), the case studies selected include additional manufacturing challenges such as monolithic wall thicknesses up to 280mm and a total infusion height of up to 6m. As a result, existing wind turbine blade manufacturing processes cannot be applied to these case studies without further modification.

1.4.1.3 Prepreg layup

For prepreg materials, an autoclave or vacuum bag and external heating is used to consolidate and cure the laminate on the tool. This process typically produces higher quality laminates with better structural properties compared to VARI, however this comes at the expense of higher production costs. Prepreg materials are more expensive and have shorter shelf lives than separated dry reinforcements and liquid resins. Furthermore, these materials must be stored in a sealed, low temperature environment to prevent gradual cure of the resin. However, as prepreg manufacturing is a simpler process than VARI, it offers lower financial risk and process development time, making it well suited for small batch and prototype production.

Ovens are typically used to achieve cure cycles at 80°C or higher for high performance marine applications. As a result, prepreg structures are generally limited in size to fit within these ovens. Airborne UK has experience manufacturing tidal turbine blades using these materials, such as the 8m blades used for the Seagen tidal turbine which was installed in 2008 (Institute of Mechanical Engineers, 2020). Prepreg materials were suitable for manufacturing tidal turbine blades as these products were typically developed and supplied as prototypes. GTM Composites manufacture prepreg carbon/epoxy rudders for racing and cruising yachts (GMT Composites, 2020), whilst CCI produce various autoclaved posts and spars for boats and yachts (CCI, 2020). Inasmet also investigated using prepreg materials for fishing vessel propellers, but after creating a prototype they concluded that a resin transfer moulding procedure would be better suited to meet commercial requirements (JEC Composites, 2011).

1.4.1.4 Resin transfer moulding

Resin transfer moulding (RTM) utilises closed rigid tooling and pressurised resin injection systems to create parts with higher volume fractions at rapid production rates and with a greater level of control over part geometry and process repeatability. RTM tooling can be expensive and impractical for larger products, so this process is best suited to high volume production of parts less than 5m in size. As with VARI, RTM is most applicable to continuous production, although the rigid closed tooling provides less scope for process flexibility or modifications. Airborne manufactured a series of composite propeller blades for a minehunter using RTM (Composites World, 2011). In this application the size, structural requirements, and the need for a good surface finish on all sides meant that RTM was the most suitable manufacturing option.

1.4.1.5 Areas for further development

The review of suitable manufacturing processes highlights a key gap in the technical capabilities of composites production. Manufacturing large composite hulls (50-100m) was identified in the UK Marine Industries Technology Roadmap as being a key technical capability that must be developed. It is apparent that there is currently no commonly applied production technique for creating large, affordable, and high-quality composite structures for marine applications.

Hand lamination and spray-up processes can be used to create a wide variety of large structures, although one must accept lower mechanical properties, and thus heavier and less structurally efficient products. Large vessels (50m+) manufactured using these processes are not likely to be competitive against existing steel assemblies when life-cycle costs are considered. Prepreg materials are too expensive and achieving high temperature cure cycles could be impractical at this scale. RTM processes are also not practically suitable at this scale due to challenges with scaling up the tooling.

VARI appears to be the most suitable manufacturing process for creating large ship hulls; however, there is no evidence of this technique being used to produce components greater than 50m in length. It is very difficult to obtain a complete understanding of the current level of technical capabilities across the globe as companies and military organisations do not wish to reveal the details of their production processes. A patent exists that describes a hybrid composite/steel hull of similar scale (Barsoum, 2005), and expired patents describe resin infusion procedures that can be applied to large composite structures such as boats (Seemann, 1999) (Seemann, 1990), but no current patents referencing specific procedures for manufacturing large composite hulls greater than 50m could be found. This indicates that the challenge primarily lies within the successful commercial application of pre-existing resin infusion technology. As the length of a vessel increases, so does the structural loading, height, and sectional thicknesses. Scaling up the infusion process is therefore not a simple task, as increases in part height and thickness will result in a significantly more complex procedure. The success of a VARI process is heavily dependent on the speed and direction of resin flow through the preform. Increasing the geometric complexity of the preform can lead to a greater risk of irregular or unpredictable resin flows, which can result in potentially large defects forming, and thus costly repair procedures, or completely scrapping the part. Scaling up the VARI process therefore increases financial risk, and considering the cost of producing 50m+ vessels, it is no surprise that shipyards are not willing to be burdened with this enormous financial risk.

1.4.2 Materials Selection, Testing, and Durability

Composite materials have seen a wide and varied use in marine structures, ranging from boats and yachts to more recent developments such as tidal current energy devices (Institute of Mechanical Engineers, 2020) and composite passenger ferries (Brødrene Aa, 2017). One of the main reasons for the popularity of composite materials in these applications is their greater long-term durability in marine environments compared to metals.

Durability concerns the longevity of the material; how well it copes with harsh environments and retains its mechanical properties over an extended period of time (otherwise known as ageing). Harsh environments can include a combination of vast temperature ranges, fire, impact and fatigue loading, erosion and wear, and moisture absorption. The latter is a critical element of long-term ageing for submerged structures such as hulls and tidal turbine blades.

The behaviour of metal alloys in marine environments is well understood and can be predicted quite accurately due to their long history of use and availability in standard material grades. Composites do not benefit from these advantages, so their long-term behaviour in marine environments is less understood. This issue is made worse as new resins, fibres and sizing materials are continually released, often with slight chemical alterations that can change laminate properties and ageing behaviour. Extensive coupon testing and conditioning programs must be carried out on any new or modified material prior to its use in manufacturing projects, a process which is both costly and time consuming (Jaksic, 2018). There is currently no alternative to this lengthy process, so designers are often pressured to stick with older materials that they know well, potentially restricting innovation.

Uncertainties in long-term properties of submerged composite structures have meant that these products are typically designed in a conservative manner, resulting in heavier and more expensive structures (Dawson, et al., 2018). Greater accuracy in predictive methods can result in lower levels of uncertainty and financial risk. This is especially true for tidal turbine blades, which must be able to operate in harsh submerged environments for 30 years with minimal maintenance.

Moisture absorption into the composite laminate is a primary cause for material degradation in submerged applications (Schutte, 1994). Polymer resins can absorb moisture slowly over time until they reach a point of saturation. Moisture absorption has been shown to be dependent upon ambient temperature, pressure, water quality/composition, resin chemical composition and the manufacturing process/quality (presence of voids) (Dawson, 2016) (Surendra Kumar, 2007) (Colin, 2014) (Carlsson, 2016). Moisture absorption, and hence material degradation may therefore vary significantly from one application to another, meaning accurate predictions of long-term durability can be difficult. Designers generally use conservative knockdown factors generated from representative material tests to account for this uncertainty in commercial projects.

These tests generally feature accelerated conditioning and mechanical testing of material specimens. Representative laminates are often conditioned in seawater between 15°C and 45°C until saturation occurs (Davies, et al., 2018) (Jaksic, 2018) (Dawson, 2016). Raising the temperature accelerates the moisture absorption process; however, it is important to remain below the wet glass transition temperature of the resin in order for the test to be representative. Coupons can be held in the conditioning unit for 6 months or more until saturation occurs. As a result, the process of determining material degradation can be lengthy and costly. This significantly increases the complexity of selecting suitable materials for a commercial project, as these tests would be required for each resin and fibre combination. For critical marine structures such as hulls and tidal turbine blades, accurate prediction of laminate degradation is crucial. Improvements to this process should be investigated to reduce the time and cost of determining material properties without compromising the accuracy of results.

1.4.3 Design Standards and Certification

Design standards are crucial elements of the product design that help to ensure structures are designed to a sufficient level of safety and robustness. Design standard authorities such as the International Standards Organisation (ISO) publish a range of standards relevant across a range of industries and applications, including shipbuilding and marine structures (ISO, 2020). Organisations such as Lloyd’s Register and Bureau Veritas develop rules and regulations for various marine technologies, whilst also providing consultancy services to help to ensure products meet both their own rules and relevant international standards. Depending on the application, customers may request that the design is granted approval from the relevant regulatory body. For more novel applications such as tidal turbine blades, there may be fewer relevant rules and regulations available to guide the designer. In these situations, regulatory bodies may work with designers to develop suitable rules. It is important that international rules and regulations continue to be revised as materials and manufacturing processes evolve, enabling the development new and improved products.

Composite hulls are predominantly limited to the leisure and military industries due to strict design and safety regulations for commercial vessels. Historically, these standards were developed primarily for metal structures, derived from years of testing and experience. These standards have been recently revised to allow the use of more advanced materials such as composites in primary structures, however meeting these standards can be challenging and costly. Fire safety in commercial vessels is currently one of the main limiting factors preventing the wide-spready use of composites. The design standard: SOLAS (Safety Of Life At Sea) had previously stated that structures and fire barriers must be steel or equivalent non-combustible materials, which completely prevented the use of polymer matrix materials. A recent amendment to this (known as regulation 17, 2002.) allows for alternative materials to be used, provided they grant an equivalent level of safety as metals (IMO, 2015). Proving equivalence is done via a risk-based approach, however this can be complex and expensive as there is no standard, easily applied set of rules. Each application must be analysed in detail, requiring stringent fire tests of composite structures to determine flammability, toxicity, fire retention, heat conduction, and strength degradation under elevated temperatures (CSC, 2009) (Royle, et al., 2019). In fact, it has been demonstrated that composite materials have improved insulation properties compared to steels (Gillitt, 2012). Even so, adoption of composites in commercial vessels has been very slow, because, unlike for previous regulations, there are no quick and easily applied set of rules for determining whether a structure is suitably safe. To address this and many other issues, the RAMSSES project (Realisation and Demonstration of Advanced Material Solutions for Sustainable and Efficient Ships) aims to develop a fast-track to approval process for composite ship structures with the aid of classification society Bureau Veritas (RAMSSES, 2017). This project features 13 novel demonstrators for various composite ship structures, and aims to provide solutions for design certification, manufacturing and repair procedures, fire safety, and life cycle assessments.

Uncertainty around fire safety regulations for commercial vessels has also led to global political disagreements. Seafaring vessels travel throughout the globe, operating in both national and international waters, and must therefore abide by the rules and regulations that govern both. Nations must agree on suitable rules to address this complex topic for numerous types of commercial vessels. Even so, the advantages of composite materials have been demonstrated with smaller passenger vessels currently sailing within national waters in Europe (Brødrene Aa, 2017).

The development and certification of novel composite products such as tidal turbine blades pose a slightly different challenge. The lack of extensive regulations combined with the wide variety of designs mean that regulatory bodies are often more involved in the design process. Designers must demonstrate a comprehensive understanding of the specific application, with extensive material testing programmes being conducted to acquire accurate predictions of material and structural behaviour during long-term operation in a marine environment. Whilst fire safety is not a primary concern for this application, other factors such as material degradation and structural fatigue can have a significant impact on the longevity and commercial viability of the structure. Approval from a relevant regulatory body would demonstrate that the design meets the operational requirements.

1.4.4 Cost and Financial Risk

Commercial viability is crucial for any marine application and is typically demonstrated by considering the entire life-cycle costs of the product. Whilst composite materials may allow for lighter, more durable structures that enable lower operational costs through reduced maintenance, repair and fuel consumption, the use of these materials typically result in higher design and manufacturing costs. To make large composite structures more commercially competitive against steel assemblies, further developments in manufacturing technologies should be investigated to reduce manufacturing cost and complexity. As outlined in Section 1.3, project development costs for the selected case studies are predicted to be of the order of billions of dollars. The production cost of a 75m composite hull shell is predicted to be over £1 million (see Section 5.17). Manufacturing process failures may result in part scrappage or costly reworking activities, with a potential loss of up to the total production cost. The novel manufacturing challenges and high costs associated with the selected case studies lead to considerable levels of financial risk.

The manufacture of composite structures is typically a more complex process compared to the assembly of steel structures due to the wide variety of available materials, manufacturing methods, and process parameters that are available. Handling and processing composite materials can be complex as small errors or uncontrolled process parameters can lead to considerable reductions in mechanical properties that diminish the advantages of these materials. Because of this, composite manufacturing processes are typically manual procedures that require a skilful and knowledgeable workforce. High-skilled labour is expensive, and when combined with the necessary infrastructural investments for composites processing (such as tooling, ovens, clean rooms etc…) can create a significant financial barrier that can deter some manufacturers based in the steel industry.

Recent developments in automated composites manufacturing may be able to provide reductions in manufacturing costs by increasing process efficiency and reducing labour costs. However, this technology will require even greater capital investment, creating a higher financial barrier for some companies. Furthermore, the complexity of composites manufacturing procedures means that implementation of automated solutions, which are more suitable for simple, repetitive tasks, is very challenging and may require modifications to product designs and materials. Automated technology has not yet been applied to the commercial manufacture of large composite marine structures, and very few general automated composites manufacturing lines currently exist on the market (Airborne, 2020) (Mikrosam, 2019) (PINETTE P.E.I., 2020). This indicates that further work is required to develop market-ready automated manufacturing solutions.

The financial risk resulting from the novel manufacturing challenges and high costs must also be addressed. For tidal turbine blades, the introduction of a new technology coupled with high installation and potentially unplanned maintenance costs create a somewhat uncertain financial situation that may deter investors and operators. In the case of shipbuilding, replacing steels with composite materials will result in high capital investment for the shipyard and vessel operator. Changing the primary structural materials will also result in greater risk for the vessel owner and operator, as the long-term performance of large composite vessels have not been physically proven in real applications. Implementing composite materials within large commercial vessels therefore requires the manufacturer, owner, and operator to all be convinced that the level of risk is acceptable.

1.4.5 Sustainable Design, Operation and Disposal

Current trends indicate that the use of composite materials in critical marine structures will continue to expand, in many cases replacing steels as key structural materials. Whilst this may provide numerous operational benefits for a variety of marine applications, the end-of-life options for these structures are somewhat limited. Thermoset resins and glass/carbon fibres are the most common types of constituent materials used in these applications due to their ease of processing, mechanical performance, and long-term durability in marine environments. Durability can be advantageous during the product's operation, however at the end of a product's life, this trait can make it difficult to dispose of the structure in a responsible and sustainable manner.

End-of-life options are already an issue for smaller composite boats. It is estimated that there are 6.3 million composite boats in Europe with life spans of between 20-30 years, and approximately 60-80k boats cease operation every year (Boatcycle, 2017). It is the owner's responsibility to dispose of their boats, however the cost of transportation and disposal leads many irresponsible owners to abandon their vessels in ports and riverbanks. With no reliable way to track down the owners of these abandoned vessels, it falls on the councils/government to dispose of them.

Concerns around sustainable end-of-life options are not only limited to marine applications. For example, EU legislation introduced in 2015 states that 95% of automotive vehicles must be recovered and reused, and 85% recovered and recycled (Council of the European Union, 2000). Therefore, any use of composites in the commercial automotive industry must support recycling. Whilst these rules do not apply to marine structures, similar legislation is expected at some point in the future.

Increased awareness of the effects of climate change and pollution have led to a greater global interest in sustainable product design, operation, and disposal. The following options, from highest to lowest priority, can be applied to reduce the environmental impact of commercial products.

- **Reduce** material usage during product manufacture.
- **Reuse** the product for another application.
- Break down the product and **recycle** the constituent materials.
- **Incinerate** the product, preferably with material and/or energy recovery.
- Responsibly dispose of the product in a dedicated **landfill** site.

In composite manufacturing processes, the total amount of materials used can be reduced through improved product designs and reduced material scrap. The latter can be achieved with better materials management and efficient ply nesting and cutting solutions (Autometrix, 2020). Recent developments in 3D printing of composite materials have the potential to significantly reduce material wastage (Andrey V. Azarov, et al., 2019) (Markforged, 2019) (Continuous Composites, 2019). Even so, reducing materials usage in production does not address the limited end-of-life options.

Reusing a composite product may be more challenging, as composite structures are typically manufactured as single parts for a specific function or purpose. Furthermore, it is very difficult to retrospectively predict the structural properties of a composite product that has been exposed to a marine environment, as there is usually no indication on the structure as to what constituent materials were used for its construction. A lack of records describing the structural loading or environmental exposure over the product's lifetime further add to the uncertainty of the state of the materials. For these reasons, reusing composite structures is very rare.

Recycling composite materials is a complex challenge that has been of increased interest in recent years as composites become more widespread. The use of non-recyclable thermoset resins and glass/carbon fibres in many marine applications means that it is generally difficult to find suitable recycling solutions. There are three primary methods for recycling these materials (Pickering, 2005):

Mechanical recycling is the simplest form of recycling in which the composite is ground up into a fine powder. The resin and fibres are not separated so the resulting powder is of limited use; mostly as a second-grade material such as fillers.

Thermal processing prioritises the recovery of fibres over the resin, as they are generally the highest value component in the composite. Fibres recovered with these processes are typically 5-25mm in length. High temperatures (400-700°C) are required to separate the components which can reduce the tensile strength of glass and carbon fibres by 50-90% and 20% respectively. Pyrolysis is primary used to recover carbon fibres as the knockdown in glass fibre strength is too high to justify the cost.. Fluidised bed and pyrolysis are two examples of thermal processes that can be used to recover fibres.

Solvolysis uses a mixture of chemicals to separate the resin and fibre components. Fibres can be recovered with approximately 90% of their initial virgin strength; however, the high cost and limited availability of the reagents required for this process combined with the hazardous materials that are produced mean that this approach is not easily applied in industry.

Recent research suggests that a new electrochemical method (electrolysis) may be a suitable alternative (Sun, 2015). The process is simple, uses widely available materials and produces fibres with 80% recovered virgin strength. However, this process is slow with a total duration of approximately 24 days. Understandably, there are concerns over the applicability of this process within a commercial setting, as thermal and mechanical recycling processes are much quicker.

Mechanical and thermal recycling are the two most commonly applied processes for recovering useful materials from manufacturing scraps and existing structures due to shorter turnaround times, relatively low costs, and flexibility in processing a range of composite materials. Even so, recycling composites is still a small industry due to the limited number of applications for recycled composite materials. Processing costs combined with reduced mechanical properties mean that recycled materials are not often commercially competitive against widely available virgin materials. Furthermore, the lack of traceability detailing the specific materials used in a 30-year-old product lead to further uncertainties over the fibre quality and mechanical properties. As a result, fibre recovery is primarily limited to manufacturing scraps instead of old, unused structures. These recovered carbon fibres may be used to create sheet moulded compounds (SMC), whilst old glass fibre structures can be mechanically grounded into powder and used to reinforce concrete buildings.

There is currently no simple solution for sustainably disposing of existing composite marine structures. It may be beneficial instead to consider alternative, more sustainable constituent materials such as natural fibres, bio-resins, and thermoplastics. However, these alternative materials also exhibit some major disadvantages. Natural fibres are very susceptible to moisture degradation, and as a result their application has been limited to a few small case studies, including the all-flax composite trimaran (Flaxcomposites 2014), and the jute reinforced bio composite sailboat (De Mony-Pajol and Cail 2014).

Thermoplastics require high processing temperatures, which can be a major limitation when producing large structures. Elium resin, developed by Arkema, is a recyclable acrylic resin that can be processed at room temperatures like a standard thermosetting resin (Arkema, 2020). When cured, the Elium resin forms a matrix that can be broken down with heat into monomers, which can be used to create new batches of resin. Research is currently being conducted to determine the best methods for recycling this material.

The sustainable disposal of large marine structures is clearly an important issue that will only become more critical as the application of composite materials continues to expand across the globe. Research is currently being conducted to understand how best to address this issue across all industries. Whilst this is an important global issue, it does not appear to be a critical limitation preventing the application of composites in large marine structures. However, future changes in government legislation should be expected, and thus sustainability is not an issue than can be ignored. At this stage, the responsible selection of sustainable materials may be the most effective route for reducing the environmental impact of large composite structures.

1.5 Focus of the Research

Two case studies have been selected that represent the main technical and commercial challenges of increased use of composites for marine applications: commercial ship hulls and tidal turbine blades. Alongside a range of technical challenges, cost and financial risk have been identified as critical factors limiting the use of composites in these applications. The literature review indicates that two of the most feasible ways to reduce cost and financial risk are through:

1. Improved methods for predicting long-term composite material degradation, which will allow reduced design margins and product development timescales.
2. More efficient and robust manufacturing procedures, which will be essential for reducing capital costs and improving production rates.

The first of these factors applies to both case studies, although the combination of high loading, harsh environment and limited accessibility means that predicting long-term degradation is particularly important for tidal turbine blades. Part of the research in this thesis addresses this challenge, with tidal turbine blades as the primary case study. The second factor is particularly important for very large-scale structures such as composite ship hulls, which also have the greatest future market and where high production rates will become increasingly important. For this reason, future design and manufacturing techniques for large composite ship hulls is the primary focus of this thesis.

Whilst the development of suitable design certification standards is currently a key challenge for large composite ship structures, this area is not directly addressed in this thesis because research projects such as RAMSSES and FIBRESHIP are currently investigating this area with the help of shipyards, certification authorities and fire safety experts. Furthermore, the key certification challenge of fire safety is a greater concern for primary ship superstructures compared to submerged structures such as the hull shell. Sustainability was also identified as an important issue; however, this is not addressed in this thesis as it does not immediately prevent the use of composites in the selected applications. It is thought that by addressing the immediate key challenges of manufacturing capability and long-term durability predictions, commercial interest in the selected applications will grow, resulting in further development of sustainable manufacturing options.

1.5.1 Aims and Objectives

The work presented in this thesis aims to answer the following overall research question:

"Is it possible to produce large composite marine structures such as tidal turbine blades and large ship hulls that are both commercially and technically viable, using where appropriate, existing knowledge, materials, and processes?"

The work has two key aims:

1. Reduce the cost and financial risk associated with predictions of long-term durability performance of composite laminates, relevant to a typical composites manufacturing company and the selected case studies.
2. Develop a manufacturing process for large composite marine structures that addresses the key manufacturing challenges and is relevant to the selected case studies and applicable within typical composites factory or shipyard.

These aims shall be achieved by meeting the following objectives:

1. Identify the limitations of existing procedures that are used in a typical composites manufacturing company to predict long-term durability of marine composite laminates.
2. Present a methodology to reduce the cost and financial risk of marine durability predictions, supported by prior research and experimental data.
3. Generate a list of acceptance criteria that can be used to guide the development of a suitable manufacturing process for large composite marine structures.
4. Gather information on existing and/or potential manufacturing approaches for large composite structures, using expert knowledge and prior industrial experience.

5. Develop a manufacturing process for a large composite marine structure using a "building block" approach supported by experimental trials and results.
6. Validate the manufacturing process via the manufacture of a full-scale demonstrator structure.
7. Review the applicability of the manufacturing process by referring to acceptance criteria.

1.5.2 Thesis Outline

The structure of this thesis broadly follows a typical development cycle for a composite product, starting with the market analysis presented in this chapter through to the development of a manufacturing production line in chapter 6. Figure 1 outlines a simplified development cycle for a typical composite product (author's own interpretation based upon experience).

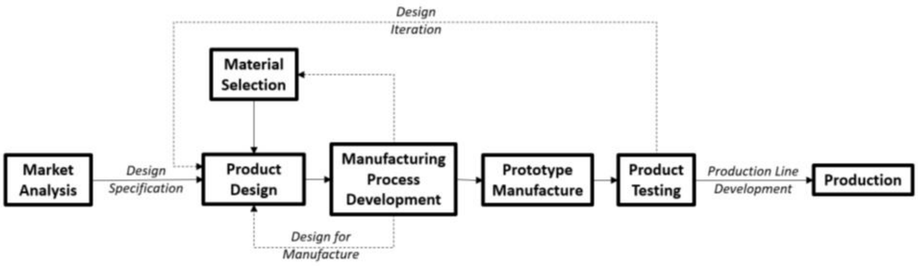


Figure 1: Development cycle for a typical composite product

The process starts with market analysis, where a suitable application or product is identified based upon existing solutions, gaps in the market and identification of potential customers. Market analysis is used to create a design specification, which defines the parameters to which the product must be designed, such as external loading conditions, quality requirements and any regulations that must be adhered to. A feasibility study is then typically conducted as part of the initial design phase to build a financial justification for the future development and manufacturing costs.

Suitable materials must be selected to meet the structural and financial requirements of the project. For composite materials used in marine applications, this process can be complex and time-consuming due to the wide range of available fibres, resins, manufacturing processes, and predicted service environments. Extensive material testing programs and predictive methods are therefore required to determine representative long-term material properties. This is explored in chapter 2.

For composite structures, the product design phase is heavily integrated with material selection and manufacturing process development. Unlike with metals, there are no standard grades of composite materials, so the manufacturing process will ultimately impact the final structural properties of the part. The complexity of composite manufacturing processes also increases the risk of defects in the part. Designing a product to accommodate a specific manufacturing process can help to alleviate processing issues, thus producing a stronger and more durable structure with fewer quality issues. This is typically referred to as “design for manufacture” and forms the basis for chapter 3 of this thesis. Product design methodology and certification are not featured in this thesis.

A prototype is typically manufactured to validate and improve upon the proposed manufacturing process. Chapter 4 details the development of a manufacturing process for a large composite hull shell, whilst chapter 5 outlines how this process was applied to manufacture a full-scale prototype demonstrator. This prototype is also used to valid the product design through structural testing, which may be required for product certification. The findings of the manufacture and testing of this prototype can be implemented back into the product and process design.

Finally, after a technically feasible and manufacturable solution has been developed, a production line must be designed to accommodate financial and commercial requirements. Modifications to process steps, infrastructure and factory layout may be implemented where appropriate to improve production efficiency. In some cases, more drastic modifications to the manufacturing process, such as the implementation of automated robotic equipment may be required to meet commercial needs. Chapter 6 explores this option in further detail for the hull shell manufacture.

The research presented in this thesis was conducted using a “Plan, Do, Check, Act” approach (PDCA), consisting of the following four stages:

1. **Plan:** An existing issue or new opportunity is first identified. Suitable solutions are analysed, and a plan is generated to implement the most suitable modification or methodology.
2. **Do:** The planned modification or methodology is implemented within small, yet representative tests. Relevant experimental data is recorded during these tests.
3. **Check:** Experimental data is used to analyse the level of success of the implemented modification or methodology.
4. **Act:** Act accordingly depending on the results of the previous stage. Implement the modification or methodology if the data indicates it was a success. If the data indicates a failure, repeat the cycle from stage 1. The cycle can be repeated numerous times to further refine the solution.

This approach was selected due its flexibility and applicability to a wide range of research challenges. This approach has been used to identify potential improvements in current composite durability prediction procedures in industry whilst also enabling the rapid development of a full-scale manufacturing process for a composite hull.

2 DURABILITY TESTING AND EVALUATION OF MARINE COMPOSITES

This work was published in "Marine Composites Design and Performance, Chapter 4: Durability Testing and Evaluation of Marine Composites, Parks & Harper, p.85-114, Copyright Elsevier 2019". This chapter is a slightly updated and modified version of the previous publication.

2.1 Introduction

Creating durable composite structures for long-term operation in marine environments can be a challenging task. As outlined in Figure 1, following the selection of a suitable application (via market review), it is critical that a design specification is constructed to clearly define the technical requirements of the product. This is typically done at the start of the design process by the customer/end user, product designer and manufacturer. During this phase, requirements such as product cost, weight, predicted structural loading, operational lifespan and environment, and other requirements featured in relevant certification/regulatory publications are collated into a single document. In the case of more novel applications where there may be a lack of relevant certification procedures, relevant certification bodies may be involved to help define product requirements, potentially based upon similar, existing products and applications. Definition of these requirements is crucial for identifying any gaps in current knowledge and the details of any necessary testing programmes. For submerged marine applications, the combination of high structural loading, harsh marine environment, and long service life result in the need to accurately predict the effect of moisture degradation on the structural performance of composite laminates.

The ability to predict the long-term degradation of composite laminates in a marine environment is crucial for designing safe and efficient marine structures. The mechanisms of laminate degradation in seawater are complex and difficult to predict using numerical methods. Therefore, physical tests are currently the most reliable method for acquiring accurate and representative durability data. This can be costly and time-consuming as it requires the manufacture, conditioning, and mechanical testing of numerous specimens. The wide variety of resin and reinforcement products available on the market, combined with the numerous manufacturing processes and process variables further add to the complexity of this challenge. It is common for organisations to conduct durability testing on representative laminates to capture all of these variations for a specific application. However, this extensive testing program means that selecting suitable materials for a specific marine application can be a daunting task, especially for companies with no prior laminate data of their own.

This chapter will begin by briefly exploring the loading and durability requirements for typical marine structures, and how these can influence material selection. The effect of moisture absorption on laminate mechanical properties is discussed, and test data is presented to show these effects. The importance of physical testing is highlighted alongside a description of current accelerated conditioning techniques and durability testing. A summary of recent testing is also presented to investigate the extent to which ageing can be accelerated further in a manner representative of the in-service environment. Finally, the reader is introduced to a number of numerical methods that could be used alongside, or potentially in-place of current testing procedures, to reduce the future cost and duration of high-performance composite commercial development projects.

2.2 Loading and Durability Analysis

Selection of suitable materials is a critical step towards a successful structural design. To do this effectively, the designer must understand the operational loads and environment. Most marine structures are subjected to high static and fatigue loads and must maintain their mechanical properties over long in-service lifetimes, often in excess of 20 years. The common environmental concern for all submerged marine structures is moisture absorption and its negative impact on mechanical properties. Other environmental issues such as fire and elevated service temperatures may also be of concern to the designer.

2.2.1 Fire requirements

Fire safety is a key design consideration for commercial ship structures and has been an issue of great interest for many years as organic resins are naturally flammable and may release toxic fumes during combustion. The risk of fire poses serious implications for commercial and civilian vessel designs. Much research has been done to investigate and improve the fire resistance of composite materials for these applications. Two options are open to the designer; one can either aim to achieve sufficient fire resistance through suitable resin and fibre selection, which can negatively impact cost and in-plane laminate performance. Alternatively, one can apply additional fire insulation, traditionally comprised of mineral wool, although new ceramic blankets are available offering reduced weight (CSC, 2009). Additional insulation can add to the weight and cost of designs, reducing the benefit of using composites over steels.

2.2.2 Temperature

Ocean temperatures are typically within the range of 0 to 35°C. This is a fairly narrow range of moderate temperatures, indicating that thermal loading is not a design issue for such applications. Furthermore, sea temperatures become even less variable with depth, so for deep sea applications, temperature is even less of a concern.

Moisture absorption acts to reduce the Tg of a composite laminate (this will be discussed in a later section). Therefore, it is important to ensure the wet laminate Tg remains above the maximum ambient service temperature. Typical marine resins can exhibit glass transition temperatures (Tg) in the range of 70-120°C (Wessex Resins, 2018) (Gurit, 2020) (Derakane, 2009). The glass transition temperature is dependent not only on the resin formulation, but also the applied cure and post-cure cycles. Therefore, laminate Tg is a variable that can be modified by the designer and/or manufacturer to meet the product specification. The fairly narrow range of low temperatures typically seen in most marine environments mean that special considerations for temperature are rarely required for these applications. As a result, Airborne UK generally use laminates with Tg values ranging from 80-100°C for submerged composite structures.

Fire safety requirements also dictate that certain ship structures must be able to withstand high temperatures. Fortunately, composites are naturally good insulators, especially in the form of foam-cored sandwich panels. Research has shown that it is possible to meet fire safety requirements with such panels (CSC, 2009).

2.2.3 Moisture absorption and degradation

Moisture absorption of sea water is common amongst all applications and will therefore be the main focus of this chapter. Most materials are affected to varying degrees by submersion in sea water. For example, steels typically corrode, and in the offshore oil and gas industry, a simple approach to tackling this issue in steel risers is to allow corrosion to occur in additional sacrificial layers of material (Melot, 2018). One can then predict with reasonable accuracy the rate of corrosion and therefore estimated life of the component.

Composite materials absorb sea water, and whilst there may be no visible degradation, this typically results in a reduction in mechanical properties. There are three major mechanisms by which water can enter a fibre reinforced composite laminate. The first, and primary mode of moisture transport through a composite material is diffusion within the resin matrix, in particular at the fibre/resin interface. Moisture also moves through the composite by two other modes: capillary transport between the fibre and matrix, and movement through any micro-cracks in the matrix. These two processes are considered to occur at a much slower rate than diffusion for most composite materials (Dhakal, H.N., et al., 2016). There are many mathematical models of varying complexity that can be used to predict the overall moisture absorption behaviour in composite materials. Fick's law is one of the simplest tools and is widely accepted as being sufficiently accurate to describe the diffusion process, and hence overall moisture absorption process in composite laminates for most industrial applications.

For Fickian absorption, the quantity of water in a laminate increases linearly with the square root of time. This is followed by a plateau, at which point the laminate has reached saturation. An example of typical experimental data showing this trend is highlighted in Figure 2 and relevant modelling techniques are discussed in more detail in Section 2.7. The data presented in Figure 2 was measured by the author using the methodology outlined in Section 2.4.

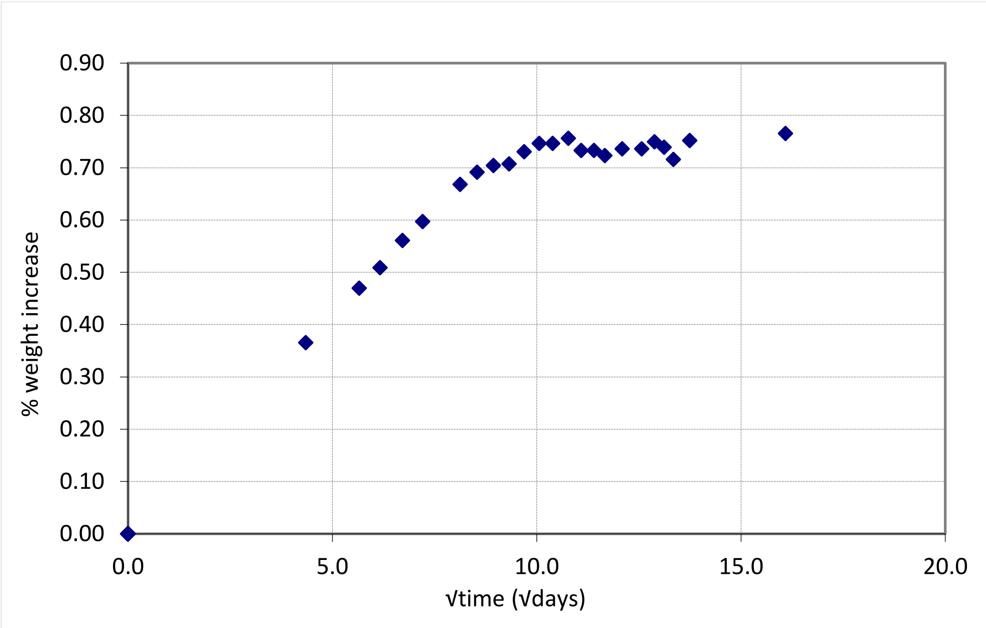


Figure 2: Typical weight gain plot due to moisture absorption for an epoxy/glass laminate

Other moisture absorption models such as Two-stage, Sigmoidal and Case II absorption can also be applied to describe non-Fickian behaviour in composite laminates (Dhakal, H.N., et al., 2016). Two-stage absorption features an initial Fickian absorption curve followed by a secondary, slower non-Fickian weight gain which results from moisture degradation of the laminate, leading to the gradual formation of voidage, and thus greater levels of moisture uptake over time (Colin, 2014) (Dhakal, H.N., et al., 2016). Sigmoidal absorption features an S-shaped weight gain curve, which also results from void formation in the laminate during moisture uptake. Case II absorption features a rapid linear absorption curve followed by an immediate plateau; behaviour that can result from the use of incompatible fibres and resin systems (Dhakal, H.N., et al., 2016). The data obtained by the author and presented in this thesis matches Fickian moisture absorption behaviour, and so these non-Fickian models are not considered further in this work.

Multiple processes occur during moisture absorption to alter the mechanical properties of the composite material. These can be characterised as reversible and non-reversible effects. Reversible effects include plasticization and swelling of the matrix, the latter of which can lead to irreversible effects such as fibre-matrix interfacial failure and microcracking due to the internal build-up of stresses

(Schutte, 1994). Composite materials may also suffer from irreversible chemical degradation known as hydrolysis. During this process polymer chains are broken apart due to the presence of H+ and OH- ions, negatively affecting the mechanical properties of the resin matrix and composite laminate. Esters, amides and imides are generally more susceptible to this (Choqueuse, D. and Davies, P., 2008). The severity of these effects depends largely on the selection of resin, fibre and sizing, together with environmental factors such as conditioning media and temperature.

2.3 Material selection

2.3.1 Resin selection

Different resin types exhibit varying degrees of sensitivity to moisture absorption and degradation. Moisture absorption not only affects mechanical properties, it also causes the resin to swell. Often, higher levels of moisture absorption are an indication of greater degradation, so it is advantageous to select resins that absorb low levels of moisture. Manufacturers' technical data sheets can provide an insight into the expected moisture absorption of neat resins, however this data is often presented in different ways, meaning comparison can be difficult. Epoxy, vinyl ester and polyester resins are the three most common choices for composite marine structures.

Polyester resins are generally not considered for high performance applications due to their inferior mechanical properties and greater levels of moisture degradation when compared with epoxies and vinyl esters. Polyester resins are commonly used for less critical applications such as the production of smaller leisure craft, where their lower cost make them an attractive choice. In such applications, resin-rich areas of more durable resins, gel coats or other protective barriers between the composite and sea water can be used to shield the internal glass/polyester laminate. This may not prevent eventual degradation, and defects such as osmotic blistering may still occur (Clegg, 2006). Searle and Summerscales present a detailed discussion of osmosis and blistering in composite laminates (Searle & Summerscales, 1999).

Both polyester and vinyl ester resins contain styrene, resulting in harmful vapour diffusing from the laminate during cure. This potential health risk to employees requires expensive fume extraction and protective safety equipment. Even with these precautions, the smell of styrene is often clearly apparent on the factory floor. High styrene content resins are therefore less preferred.

Vinyl esters typically sit between epoxies and polyesters in terms of mechanical performance and cost. These resins exhibit relatively low moisture absorption values, supporting their traditional use in boatbuilding and other marine structures. Processing of these resins is also more tolerant to variations in catalyst/resin mixture ratios. Furthermore, their improved resistance to harsh chemicals and environmental degradation over polyesters make them suitable for a wide range of marine applications. Ashland provides a guide detailing the comparative resistance of their vinyl ester resin grades to various chemical environments (Ashland, 2016).

Epoxy resins tend to offer greater mechanical properties than either vinyl ester or polyester resins and are generally only used for high performance structures due to their higher cost. Processing epoxy resins is slightly more challenging due to the tight tolerances required for hardener/resin mixture ratios. Even so, epoxy resins are widely used as they can also offer greater resistance to environmental degradation.

More recent developments in polymer chemistry have produced resins that process like vinyl ester resins but offer similar mechanical performances to epoxies. To reflect this, these resins are marketed as epoxy-vinyl ester resins. Two examples of such marine-grade resins are Dion 9100 and Derakane 8084. Both resins have been approved by DNV-GL for production of ship structures.

2.3.2 Fibre selection

Carbon and glass are the two most common fibre types for high performance marine applications. Glass fibres are generally preferred for less critical applications where cost is a key driver, whilst carbon fibres can provide laminates with superior strength and stiffness properties, resulting in more efficient structures at a higher cost.

To achieve the necessary strength to weight ratios required in high performance applications, laminates with continuous aligned fibres are generally used over alternatives such as chop strand mats. Continuous aligned fibres allow for the construction of optimised laminates, the orthotropic properties of which provide a significant advantage over steels, justifying the often greater manufacturing costs.

Fibres are the major contributor to the laminate mechanical properties, and therefore fibre degradation is an important consideration when selecting suitable materials for marine applications. The vulnerability to moisture degradation varies among the range of available fibres. Whilst carbon fibres are susceptible to chemical attack, they are generally inert in sea water at moderate temperatures (Echtermeyer, 2018). Unprotected glass fibres on the other hand suffer a reduction in strength when exposed to sea water. This effect is reduced if the fibres are protected by a resin matrix, which is true for most applications. Nevertheless, designers often select glass fibres, accepting the greater vulnerability to moisture degradation. In some applications it is simply not commercially viable to select carbon fibres, and in others a combination of glass and carbon fibres may be used as the best compromise between cost and performance.

Glass fibres are available in various different grades; selected based upon their properties and the specific application. E-glass is the most affordable, and widely used grade of glass fibre. S-glass fibres offer greater tensile strength but come at a higher cost. E-CR glass, a boron-free glass variant, offers improved chemical and electrical resistance. Renaud and Greenwood demonstrated that the advantages of utilising E-CR glass are more apparent when materials are exposed to either acidic/alkaline solutions or tap/deionised water (Renaud & Greenwood, 2005). Nevertheless, this study still indicates that E-CR glass is more corrosion resistant than E-glass in sea water environments. Conversely, Kennedy, Leen at al. found that both E-glass and E-CR glass/vinyl ester laminates experienced similar reductions in tensile strength after a 30-month conditioning period in sea water at 40°C (Kennedy, 2016). Thus, the true cost benefit of using E-CR glass over E-glass for marine applications is unclear.

Recent concerns regarding the environmental impact of composite structures has fuelled a growing interest in more sustainable materials. Natural fibres can be sourced from many different plant species, and Sanjay et al. provide an overview of the typical properties of each type (Sanjay, 2018). Hemp and flax are common choices, and multiple papers have investigated the effects of water submersion on these materials (Yan, 2015) (Cheour, 2016). A major disadvantage with natural fibres is their susceptibility to moisture degradation, which has restricted their use in many structures requiring long term durability. However, it has been demonstrated that fibre treatment can reduce this effect (Lui, 2017). As of today, the application of natural fibres in the marine industry is limited to a few small case studies; examples include the all-flax composite trimaran (Flaxcomposites, 2014), and the jute reinforced bio composite sailboat (De Mony-Pajol, 2014).

2.3.3 Sizing selection

The choice of sizing (interface coupling agent) can have considerable impact on not only the immediate static performance, but also the long-term durability of a composite laminate. As water enters a composite laminate, it acts to degrade the interface between the resin and fibre. It is therefore crucial that a good bond is formed between resin and fibre, which can be achieved through both well controlled manufacturing processes and selection of a compatible sizing. It has been demonstrated that degradation of the sizing on rolls of dry fibres can also occur over time depending on storage conditions (Peters, 2016). Sizing degradation can result in a poor fibre/resin interface, impacting laminate mechanical performance. As this is predominantly an issue concerning the chemical formulation of the constituents, it is extremely difficult for engineers to predict the effect of sizing selection without extensive coupon testing.

2.3.4 Manufacturing processes

It is also important to consider how the manufacturing process may affect the mechanical performance and durability of a composite structure. The manufacturing process is generally limited by other factors such as cost, size of the structure, available equipment and capabilities, material availability and existing material durability data. For example, the higher cost of prepreg materials often prevents them being used in large marine structures with high material volume. Furthermore, the high temperature curing requirements of prepreg materials mean that structures must be able to fit inside an oven or autoclave. For larger structures this can be difficult. Infused resins generally have lower temperature curing requirements, allowing large structures to be produced within heated tents or even at room temperature. Vacuum bag infusion also offers lower material and manufacturing costs provided the process is repeatable (dependent on the knowledge and experience of the manufacturer). For these reasons, vacuum bag infusion is a common manufacturing process for high performance marine structures. Alternatively, open contact moulding, a process more commonly used in boatbuilding, is arguably the simplest method for manufacturing a composite structure. However, the resulting laminate properties are significantly inferior to vacuum bag infusion and prepreg, both of which can fully exploit the advantages of composite materials. Also, increasing concerns for workers health and safety have led to a push away from open layups towards closed infusions to limit human exposure to hazardous chemicals and vapours.

2.3.5 Challenges facing the research community

A significant amount of academic research is still being conducted to investigate the moisture degradation of various composite materials (Davies, et al., 2018) (Cheour, 2016) (Dawson, 2016) (Tual, 2015) (Humeau, 2016) (Guermazi, 2016). However, it is highly likely that this process of understanding marine composite durability behaviour is being complicated by the wide range of commercially available fibres, resins and sizings, combined with potential variations in laminate mechanical properties due to manufacturing processes. As resin and fibre suppliers continue to improve their products, older versions become obsolete and more difficult, or even impossible to obtain. Design engineers can also be pressured to utilise the most advanced and/or widely available materials to enhance product performance or reduce costs, gaining an edge over competitors. These considerations, combined with the wide range of marine applications, mean that it is difficult for academia and industry to select a “universal laminate” on which to focus research efforts.

Due to these variations in marine laminates and their properties, it is unlikely that laminates produced in an industrial setting will have identical mechanical properties and moisture degradation behaviour to those quoted in literature. Furthermore, laminates produced in industry are expected to vary between companies, even for the same applications. Therefore, for high performance applications, companies often reduce risk by conditioning and testing their own laminates. These tests can also account for batch variation in constituent materials and the internal manufacturing variability of the laminates.

2.4 Current seawater conditioning techniques

The general purpose of sea water conditioning is to identify the knockdown in mechanical properties due to long-term submersion in sea water for a specified composite material, which can then be incorporated into the product design. For example, in tidal turbine designs these degraded material properties are used in place of dry material properties when performing design analysis. This is based upon the conservative assumption that in service, the entire structural laminate will be fully saturated. In practice it is difficult to predict whether this is the case after 25 years of service. Due to the combination of protective coatings, low temperatures, and thick laminates, it is entirely possible that large sections of the laminate will remain dry. However, it is difficult to verify this due to the lack of real data (inspectable sections of blades that have seen a full-service life). Where the designer is faced with uncertainty, it is better to build in reasonable factors of safety into the design. A better understanding and method of predicting the level of saturation seen in service would allow for more efficient designs.

The most accurate approach to investigate the long-term sea water effects on composite materials would be to condition samples in an environment identical to the predicted in-service environment. However, a typical service life would consist of 20-30 years submergence in sea water between 0-35°C. In an industrial setting, where companies need to conduct their own tests, it is clearly not feasible to wait this long for design data. Instead, companies use accelerated conditioning procedures to obtain this data faster.

Current sea water conditioning techniques involve the continued submersion of test specimens in water at a specified constant temperature (within ±1°C) until saturation occurs. ASTM D5229 provides a detailed overview of this process (ASTM, 2004). Moisture absorption is typically measured by periodic weighing of traveller specimens that are conditioned alongside the test specimens. Travellers are often used to measure weight gain because mechanical test specimens are generally too small to obtain precise weight change measurements. ASTM D5229 outlines a methodology which ensures that the weighing procedure of these travellers has a minimal effect on the weight gain measurements. The baseline mass of the dry travellers is recorded prior to conditioning. During conditioning, the travellers are removed from the seawater tank and immediately placed in a sealed plastic bag and left to cool to ambient room temperature. The travellers are then removed from the bag and excess surface moisture is removed using a lint-free towel. The traveller is weighed to the required accuracy as defined in ASTM D5229 (1.0mg for travellers featured in the experiments conducted by the author in this investigation) and immediately placed back into the conditioning tank. The travellers must not remain outside of the conditioning tank and sealed bag for longer than 30 and 5 minutes, respectively. Following this methodology minimises the levels of moisture desorption out of the travellers, thus increasing the accuracy of the results. Measurements are repeated periodically until the data indicates that saturation has occurred; the point at which the specimen weight reaches a point of constant mass (defined in this investigation as less than a 0.01% change in traveller mass over 7 days). All specimens featured in this investigation were conditioned in a static container of seawater that was sourced from “Blue Flag” beaches along the south coast of the UK.

2.4.1 Effect of temperature

The rate of moisture absorption into a polymer can be increased by raising the conditioning temperature. For investigations concerning the mechanical properties of saturated laminates, the conditioning temperature is limited by the Tg of the constituents. Wright showed, as a rough rule-of-thumb, the Tg of epoxy resins reduces by 20°C for each 1% weight gain due to moisture absorption (Wright, 1981). This is true for weights gains between 0% and 7%. Based upon previous experience of typical saturated weight gains of marine composites at AEL Airborne, 45°C was determined to be the maximum “safe” conditioning temperature.

Conditioning near the wet Tg can promote further degradation, affecting weight gain measurements and mechanical properties of the laminate. Previous research has demonstrated that conditioning at elevated temperatures (~80°C) can result in weight loss of the specimen after an initial linear weight gain (Guermazi, 2016). Non-Fickian effects due to elevated conditioning temperatures have also been demonstrated in (Boisseau, 2011). Similar results have been found during an internal investigation at AEL Airborne. It is thought that in this case, conditioning at temperatures near the wet Tg of the polyester stitching (50-60°C) results in a secondary weight gain after initial saturation.

Merdas et al. present a formula for predicting the wet Tg of a composite matrix (Merdas, 2001). Using this method, one can predict a knockdown in Tg for a typical epoxy marine resin (Dry Tg ~ 350K) to be 20.1K assuming 3% weight gain at saturation (of the resin only, assumed to be equivalent to ~1% weight gain in a laminate) (Davies, 2008).This shows a high degree of correlation with the above rough rule-of-thumb.

The effect of high temperature conditioning (50°C+) on specific composite materials has been investigated. It is apparent that some materials can be conditioned at temperatures of 60 to 80°C

(Tual, 2015), whilst others clearly cannot (Dawson, 2016). For industrial applications, conditioning procedures must be robust, and applicable to a multitude of relevant materials.

2.4.2 Effect of pressure

Humeau, Davies et al. have investigated the effect of hydrostatic pressure on moisture uptake (Humeau, 2016). It was found that the effect of pressure varies depending on the manufacturing process, with hand layup laminates experiencing greater moisture uptake under high pressure compared to infused laminates. Additionally, no effect of pressure on moisture uptake was observed with prepreg laminates. An increased porosity in the hand layup panels compared to the infused panels and to an even greater extent, the prepreg panels, is the major cause. The study also found that this increase in moisture uptake did not significantly affect the mechanical performance of the laminates. A previous investigation also found similar trends; with carbon fibre filament wound laminates experiencing greater saturation levels under high pressure, with little effect on mechanical performance (Davies, 1997). This study also demonstrated how increased pressure can result in a greater initial rate of moisture uptake.

These findings are interesting for deep-sea applications, as they suggest that it may be possible to avoid pressurised conditioning chambers when testing certain monolithic laminates. It also suggests that pressurising sea water chambers is not an effective method for accelerating conditioning procedures.

2.4.3 Effect of water composition

Deionised water can be used in place of sea water for conditioning procedures. This has been shown to have little effect on the initial rate of moisture uptake, however there is a significant increase in the saturation level when compared with sea water (Dawson, 2016). Therefore, conditioning processes using deionised water are thought to be more conservative than sea water. However, the use of deionised water allows better comparison of data between companies and researchers, as its composition is fairly well controlled. The composition of sea water can vary based upon when and where it was collected. Therefore, the designer must take care to source sea water from suitable locations that represent the in-service environment.

It is important to note that the sensitivity to conditioning media varies among different materials. A study by Renaud and Greenwood suggests that conditioning laminates in deionised water rather than sea water has a greater effect on the mechanical properties of E-glass compared to ECR-glass (Renaud & Greenwood, 2005). Therefore, using deionised water as a conditioning medium to investigate the long term durability of composites for sea water applications may be less suitable for laminates composed of E-glass compared to ECR-glass. It is difficult to predict these effects without conducting physical testing of specimens. For the purposes of testing multiple types of material, it is therefore much safer to condition with a medium that closely represents in service conditions.

2.4.4 Effect of testing environment

As previously discussed, composites experience reversible and non-reversible effects when undergoing sea water conditioning. For fully submerged applications, it is important to capture all of these effects during material testing.

Generally, the testing environment only significantly affects results when tests are of long duration, as moisture diffusion out of a laminate is not instantaneous. For short duration static tests it is acceptable to test the coupons in dry conditions, provided they are tested within a reasonable time of removal from the conditioning unit. For tests of longer duration, it is generally thought that maintaining the conditioning environment during testing will increase the accuracy of results. It has been demonstrated that fatigue coupons tested in air exhibit a longer fatigue life than those tested in sea water (Smith, 1996). The authors propose that water trapped within cracks in the composite are the cause of this observation. However, recent studies on a glass/epoxy laminate have shown that testing fatigue properties whilst the test specimen is submerged in water produces the same results as for a standard, dry testing environment (Dawson, 2016). These two findings highlight the wide variation and complexities of composite materials testing.

2.4.5 Effect of pH

Harsh chemicals are known to cause significant degradation of composite laminates, with the effects varying between different chemicals and composite materials. It has been shown that increasing the concentration of hydrochloric acid (HCl) in water resulted in a further knockdown in interlaminar shear stress (ILSS) of E-glass/epoxy conditioned specimens (Surendra Kumar, 2007). A 16-18% reduction in ILSS was observed for specimens conditioned in a 5% concentrated solution of HCl. This study also showed that an increase in concentration of HCl acts to reduce the moisture uptake at saturation.

Interestingly, it has been found that glass/polyester specimens conditioned in a low pH (1-2) solution experienced a slight (0-13%) increase in tensile strength (Stamenovic, 2011). The same study also shows that the same specimens conditioned in a higher pH (12-14) solution experienced a reduction in tensile strength of up to 27%.

It is therefore imperative that the conditioning environment seen by the composite specimens accurately represents the expected in-service environment. To ensure this, pH monitoring and control methods should be used. For typical marine applications a pH of 7.5-8.4, representative of fresh sea water, is desired. In closed conditioning tanks with no continuous circulation of fresh sea water, the pH can vary over time as materials such as metals corrode in the sea water. In such cases active pH control is required.

2.4.6 Effect of specimen dimensions

The specimen dimensions can heavily influence the rate of diffusion in specific directions (Beringhier, 2016). For example, a flat, thin specimen will experience a greater diffusion rate through thickness due to the larger area of the top and bottom exposed surfaces. Panels of ~3mm thick are common for weight gain measurements. In practice, it is unlikely that laminate edges will be in direct contact with sea water, and further improvements can be made to the conditioning process to reflect this. The edges of the laminate can be covered with an impermeable material so only diffusion through the faces of the laminate is possible. Alternatively, conditioning chambers can be designed to hold specimens in such a way that only one face is in direct contact with water. This is the most representative conditioning test for most marine structures.

The time for a typical composite specimen to saturate is proportional to the specimen thickness. This is due to the bias in diffusion through-thickness and means that conditioning thicker laminates will take significantly longer. This can be an issue when investigating the impact response of conditioned specimens as these test laminates are typically 10-15mm thick, representing real world structures.

2.4.7 Effects of the manufacturing process

Specimen manufacturing quality can have a significant impact on both laminate mechanical properties and moisture absorption characteristics. Rough handling of materials, especially lightly stitched dry fabrics, can result in poor laminate quality and incorrect fibre orientations. For material characterisation and qualification, it is imperative that fibre orientation within test coupons is tightly controlled. Tolerances are specified in the relevant test standards, for example ASTM D2344 defines a ply orientation tolerance of +/-0.5° with respect to a datum.

Ply orientation can also affect the moisture absorption characteristics of a laminate. As discussed previously, one mechanism for moisture transport through a laminate is capillary action between the fibres and matrix. Whilst the fibre orientation may have an initial effect on moisture absorption, it is not thought to have a significant effect once the specimen has been saturated. Furthermore, as most conditioned test specimens are thin, the primary path of diffusion is through the thickness.

Thomason demonstrated that porosity and voids can significantly increase the initial rate of absorption and the saturation level of a composite laminate (Thomason, 1995). This is of particular importance for industrial applications where manufacturing variability and batch variation can occur.

Carlsson and Du present data showing that two similar composite panels manufactured at different locations exhibit very different moisture uptakes (Carlsson, 2016). Dawson and Davies also directly compared the moisture uptake of infused and prepreg specimens (Dawson, 2016). Interestingly, these results indicate that whilst the infused laminates seem to saturate faster, the prepreg specimens experience greater weight gains at saturation.

2.4.8 Limitations of Current Ageing Procedures

One must therefore make a compromise between simulating a realistic service environment and achieving a sufficiently fast absorption rate when designing a suitable conditioning procedure. A common approach is to condition samples in seawater at 45°C. This temperature has been shown in practice to be sufficiently high to significantly accelerate the conditioning process whilst being far enough below the wet Tg to avoid causing additional degradation. In this scenario, the engineer places the importance of risk and accuracy of conditioning data over conditioning speed.

The major limitation with current methods is the elapsed time required to fully saturate specimens. It can take between 4 to 6 months to fully saturate a laminate of ~3mm thickness, which is typical for many mechanical tests. This conditioning time is added to the overall project duration, as the design process cannot be finalised without this data. By accelerating this process, the overall project duration and cost can be reduced. This in turn will improve the competitiveness of composite products against alternative materials such as steel.

It should be noted that these procedures are valid for predicting the long-term performance of composite structures exposed to relatively mild temperatures, for example, marine current turbines and ship structures. These procedures are of limited use when investigating high temperature applications such as those found in the offshore oil and gas industry, where the materials are often operating near their maximum service temperature (Echtermeyer, 2018).

2.5 Mechanical testing of saturated specimens

2.5.1 Testing methodology

In order to investigate the mechanical degradation of composite laminates in a chosen conditioning medium, specimens are tested to failure after conditioning and compared against identical, non-conditioned dry specimens.

The extent of testing required is dependent on the purpose of the tests and use of the data. To compare the moisture degradation of different laminates for the purpose of material selection, it is generally considered acceptable to investigate only two static mechanical properties:

- **Interlaminar shear stress (ILSS):** This value is highly dependent on resin properties. It is a good indication of resin and resin/fibre interface strength, and hence resin degradation when comparing dry and conditioned results. There are multiple test methods available for obtaining this property, the simplest being the 3-point bend short beam shear test. The simplicity of coupon geometry and test procedure is particularly advantageous when conducting a large number of tests in an industrial environment. ASTM D2334 and ISO 14130 provide detailed accounts of the testing procedure. Other tests are available such as double-notched shear, however coupon preparation is more complex.
- **Flexural strength:** This property is an indication of fibre and fibre/matrix interface strength, as well as fibre and sizing degradation. ASTM D7264 and ISO 14125 both define procedures for obtaining this value from three and four point bending tests. Once again, the test coupons are quite simple and therefore preferred for comparative investigations.

These two properties give a quick, and reasonably reliable indication of general laminate performance, enabling a quick comparison between different laminates and materials. It is important to understand the assumptions and limitations of both tests, even when following the test standards. The combination of specimen geometry and constituent properties will determine the proportion of directional loading within the specimen, which determines the failure mode, an essential consideration.

For detailed structural design more extensive testing is required. Generally, this will entail static and fatigue testing of various coupons and load conditions, including tension, compression and in-plane and interlaminar shear. Larger specimens can be tested separately with intentional defects such as holes and ply drops, to be more representative of real-world structures. These tests are often conducted on dry specimens as thicker coupons can take significantly longer to saturate. The separate effects of local defects and moisture degradation are normally combined during product design. Designs incorporating thick monolithic laminates may also require knowledge of out-of-plane properties.

The test pyramid describes a standard approach used in many industrial design projects. Figure 3 displays a test pyramid for a typical high-performance marine structure. A larger number of more affordable ply and laminate level tests support fewer large-scale structural tests. The entire structural design may be validated with a full-scale prototype. The goal of a test pyramid is to help the designer achieve a suitable compromise between cost and structural validation. For example, the certification standard for tidal and wave energy converters suggests supporting analytical design with material and prototype testing among others (DNV, 2008).

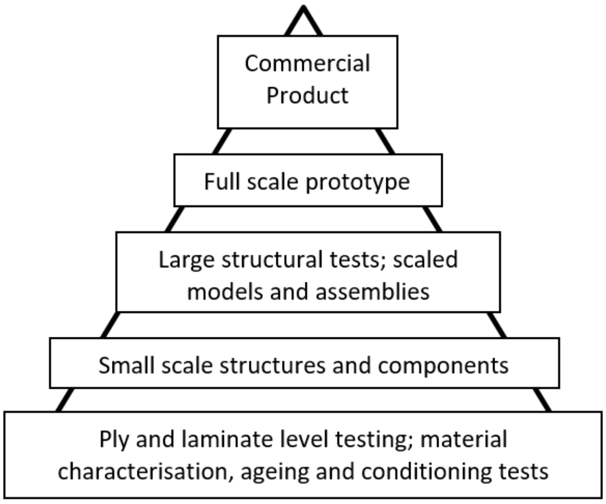


Figure 3: Typical testing pyramid for high performance marine structures

The test pyramid in Figure 3 can be thought of as a typical baseline approach for many composite structures. Further modifications can be made to improve the effectiveness of this approach based upon previous works and developments in the composites industry. The aerospace industry adopted composite materials for large, integrated high-performance structures earlier than the marine industry, so there may be some lessons that could be learned from this previous work. For example, the Composites Affordability Initiative, which was primarily aimed towards aerospace structures, identified a need for reducing the cost and risk of composite airframe structures by implementing affordable designs (i.e., reduced part count), the use of analytical tools to build design confidence, and mature manufacturing processes that are reliable and repeatable (Russell, 2007). Whilst this work is primarily focused towards large, integrated airframe structures, the generalised approach may also be applicable to large marine structures which share many of the same design and manufacturing challenges (i.e., large, complex bonded composite assemblies). Another aerospace initiative, the Accelerated Insertion of Materials, presents a methodology for accelerating the implementation of composite materials within military systems. This methodology features the implementation of an integrated product development team, technology maturation plan, existing composites design and manufacturing knowledge, test techniques and analysis tools (Hahn, 2004). In particular, this document highlights the challenges of obtaining highly accurate long-term durability predictions for aerospace structures due to the complex nature of moisture absorption and damage propagation coupling effects and the lack of highly accurate modelling and accelerated testing procedures. To account for this, the methodology features the use of durability tools to provide quantitative support to experienced designers that rely on years of expert experience and intuition. For novel composite applications, expert experience and intuition is an extremely important source of knowledge that should be implemented at the early product design stage. Tools such as Prosel, which feature a compilation of experience, lessons learned and guidance for the development of high-performance composite structures (primarily aerospace, automotive and sports applications), may be useful for reducing project costs and improving overall commercial viability (Prosel, 2020).

In the future, a greater understanding of the physical processes by which materials degrade over time in a marine environment will enable designers to replace a significant portion of the lengthy, costly test programs with faster, cheaper simulations and numerical predictions. Numerical models are being developed; however, they are at early stages and require extensive test data for validation. It has been suggested that, to help accelerate this process, as well as improve the applicability of such models for both academic and industrial purposes, a limited number of resin, sizing and fibre combinations should be selected for investigation and commercial use.

2.5.2 Static testing of conditioned specimens

Static tests are generally the simplest and most affordable form of physical material testing due to the rapid testing procedures and simplicity of test specimens. As previously discussed, ILSS and flexural strength static tests can be conducted to identify the most suitable materials for a specific application. To investigate this procedure further, a range of composite laminates were manufactured, conditioned, and tested in both interlaminar shear and flexural strength by the author in accordance with ASTM D2334 and D7264. Various fibres and resin systems currently marketed for marine applications were used to manufacture these test specimens. Table 1 outlines the materials and test specimens that were used in this investigation.

Table 1: Materials used to construct ILSS and flexural strength coupons.

Laminate ID	Stacking Sequence for ILSS/Flexural coupons	Fibres and Sizing	Resin and Hardener	Average Laminate Thickness (mm)	Average Laminate Fibre Volume Fraction (%)
Carbon/Epoxy A	$[0]_6$ / $[0]_5$	600gsm Panex 35 UD Carbon	Proset 117, M2010	3.17	62.74
Carbon/Epoxy B	$[0]_6$ / $[0]_5$	600gsm Panex 35 UD Carbon	Baxxores ER 5700, Baxxodur EC 57200	3.17	62.70
Carbon/Epoxy C	$[0]_6$ / $[0]_5$	600gsm Panex 35 UD Carbon	SP Prime 27, Prime 20 Extra Slow	3.17	62.74
Glass/Epoxy A	$[0]_6$ / $[0]_6$	600gsm Standard UD E-Glass, 111A	Proset 117, M2010	2.74	51.82
Glass/Epoxy B	$[0]_6$ / $[0]_6$	600gsm FGE708 Advantex UD Glass, SE2020	Proset 117, M2010	2.61	52.65
Glass/Epoxy C	$[0]_6$ / $[0]_6$	600gsm FGE708 Advantex UD Glass, SE2020	Araldite LY 1564 SP, XB 3403	2.64	53.64
Glass/Vinyl Ester A	$[0]_6$ / $[0]_6$	600gsm Chomorat BT640 UD Glass, SE4740	Derakane 411-200, Trigonox 239	2.89	49.04
Glass/Vinyl Ester B	$[0]_6$ / $[0]_6$	600gsm Chomorat BT640 UD Glass, SE4740	Derakane 8084, Trigonox 239	3.00	47.21

All test specimens featured in this thesis were manufactured by the author using the following procedure. Firstly, plies of unidirectional dry reinforcement were cut to dimensions 260x300mm using a CNC ply cutter (0° along 300mm direction). Plies were laid up by hand onto a pre-released aluminium tool surface in accordance with the stacking sequence given in Table 1. All laminates were manufactured via vacuum assisted resin infusion (vacuum level: -0.9 bar) under an PTFE coated aluminium caul plate (5mm thickness). Following the infusion process, all laminates were left to cure at room temperature for 24 hours, after which the vacuum consumables and caul plate were removed, and the laminate demoulded. A visual inspection of each laminate was conducted (with a backlight shining through the laminate thickness) to detect any visible defects such as voids, wrinkles, and resin rich areas. Any visible defects were clearly marked so that the affected area would not be used to manufacture test specimens. Replacement laminates were manufactured at this stage if necessary. All laminates were post-cured in an oven at 80°C for 6 hours (1°C/min ramp rate). Coupons were cut from the panels using a water-cooled diamond-tipped circular saw in accordance with the allowable specimen geometric tolerances outlined in ASTM D 2344 and 7634. Specimen geometries were inspected for defects (such as cracks or delaminations) which may have been created during the cutting process. Any specimens with visible defects were discarded. The coupons were then oven dried at 40°C for 4 hours to remove any moisture that may have been added to the specimens during the cutting procedure. Test specimens were then immediately placed in a sealed plastic bag or conditioning chamber following the procedure outlined in Section 2.4. The test specimens were then conditioned in static sea water at either 25°C, 35°C, 45°C or 55°C until saturation.

After conditioning, test specimens were placed in sealed plastic bags, excess surface moisture removed using a lint-free towel, and immediately mechanically tested to failure at ambient laboratory conditions (dry, room temperature). Un-conditioned (dry) coupons were also mechanically tested to provide a comparison against conditioned specimens. Three-point bend interlaminar and flexural tests were conducted in accordance with ASTM D 2344 and 7634, respectively. Specimen failure modes were checked against the allowable failure modes given in ASTM D 2344 and 7634. For three-point bend ILSS specimens the only acceptable failure mode is interlaminar shear (located on either side of the coupon, between the loading pins and near laminate mid-thickness, as this is typically the region of maximum ILSS. Failure initiation outside of this region may indicate the presence of one or more defects within the specimen, or an incorrect testing procedure). For three-point bend flexural specimens the acceptable failure modes are tensile or compressive (buckling) failure on either of the outer surfaces at the centre of the specimen. Examples of acceptable specimen failures are presented in Appendix A.8. Specimens exhibiting other failure modes (such as crushing under the loading pins) are neglected, as this indicates defective specimens or unsuitable specimen geometries or testing equipment. A minimum of 5 data points corresponding to acceptable specimen failures were recorded for each unique test (i.e., each laminate material and conditioning temperature combination). Figure 4 and Figure 5 show the degradation in ILSS and flexural strength for the laminates investigated.

It is important to note that the specimen manufacture, conditioning, and testing was conducted by the author at Airborne UK using equipment and apparatus available to a typical composites manufacturing company. When conducting these tests in an industrial setting, is it important to understand the purpose of the tests and how the recorded data will be used, as these factors will determine how the tests should be conducted. The investigations featured in this chapter are primarily focused on material selection in industry. Therefore, realistic manufacturing tolerances that represent feasible manufacturing procedures should be incorporated into the manufacture of test laminates to improve applicability of results.

It is therefore important to consider the applicability of standard test procedures for industrial, or "out-of-laboratory" tests. It may not be possible in an industrial setting to measure or meet some specimen requirements outlined in ASTM standards, such as allowable fibre alignment tolerances. When the author manufactured the specimens featured in this investigation, it was not possible to accurately measure the fibre alignment, and thus impossible to confirm that the ±0.5° fibre alignment tolerance was met (as defined in ASTM D2344) (ASTM, 2013). Furthermore, the light stitching holding the fibres tows together within the 600gsm unidirectional plies was insufficient in limiting fibre movement to within this tolerance during the layup procedure. It was therefore decided that this requirement was unreasonable, and standard internal laminating practices using visual inspection were employed instead. Opposite edges of the plies were aligned to two parallel datum lines on the tool surface by eye. Following the same procedures for the manufacture of test specimens and commercial manufacturing projects (where applicable) helps to ensure the test specimens are representative of commercial structures.

This coupon testing procedure could be expanded incorporate the effects of manufacturing defects that may occur on a production line, and thus generate more representative laminate data. For example, additional sets of test specimens could be manufactured with intentional defects to investigate their effects on structural properties. However, to successfully do this, it is crucial to understand whether certain defects would be compatible with these standard testing methodologies (i.e., the position and size of defects within test coupons may lead to invalid failure modes due to the small scale of test specimens). In such cases, non-standard test procedures and specimen geometries may be required. This is not investigated in this work and is instead left for future investigations.

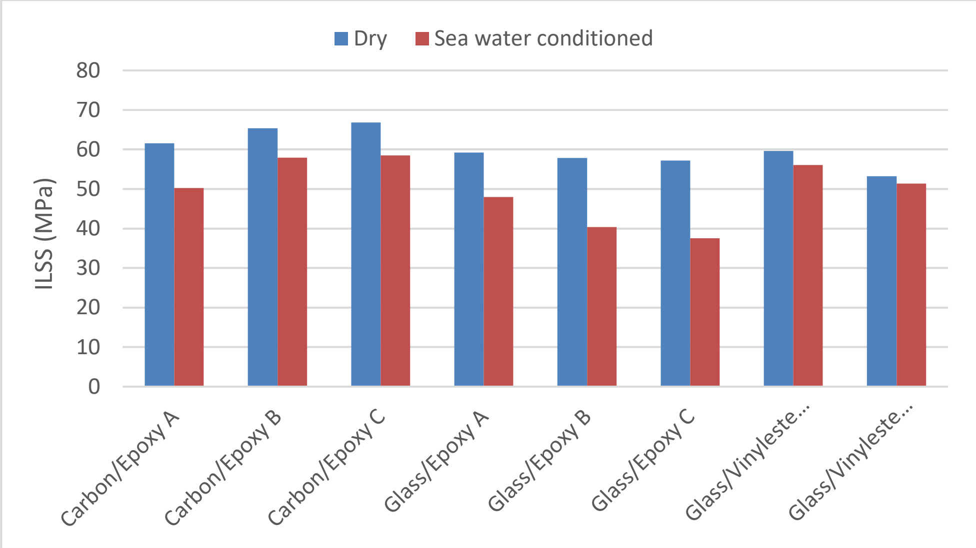


Figure 4: Comparison of dry and sea water conditioned (45°C) ILSS of typical marine laminates

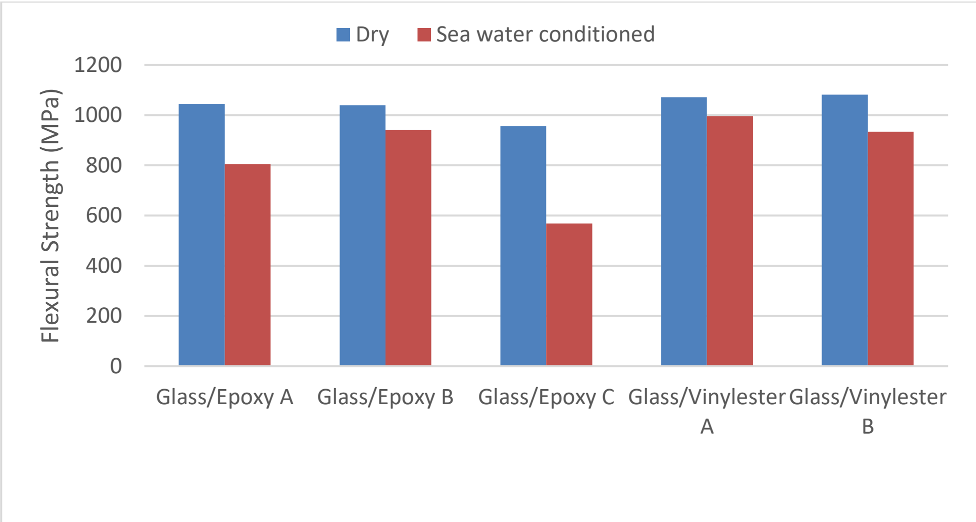


Figure 5: Comparison of dry and sea water conditioned (45°C) flexural strength of typical marine laminates

Figure 4 indicates that marine composite laminates typically experience a 5-30% reduction in ILSS after sea water saturation, and that both the wet and dry strength vary across the range of materials. In Figure 5, flexural strength appears to vary more across wet specimens, with an overall variation of 43% compared to 12% for dry specimens. For both ILSS and flexural tests, all coupons failed via acceptable failure modes (ILSS: Interlaminar shear failure at specimen mid-plane. Flexural: tensile/compressive failure on outer surfaces at the centre of the specimen). No changes in specimen failure modes were detected between dry and wet conditioned specimens.

These results indicate that moisture degradation varies significantly among composite laminates constructed from resins and fibres that suppliers claim are all suitable for marine use. This variation in material behaviour highlights the importance of material testing and selection at an early stage in the design process. These results indicate that the Glass/ vinyl ester laminates experience lower reductions in interlaminar shear and flexural strengths due to moisture absorption compared to the other resins in this investigation. Glass/vinyl ester laminate A exhibits comparable wet ILSS to carbon/epoxy laminates at a much lower cost. This laminate would likely be selected for high performance marine applications and further mechanical testing would be conducted to determine the full range of relevant laminate properties.

2.5.3 Impact testing of conditioned specimens

For some marine applications, such as military and civilian vessels, the resistance to impact damage of a composite structure can be an important consideration. Whilst higher energy impacts may be of more interest for military applications, everyday impact loads such as dropped tools or equipment may also be of interest to a wide range of general marine applications. In critical cases, it may be justified to investigate the impact resistance of representative laminates and structures using physical tests. A drop tower can be used for this test, providing a controlled impact of specified energy to a material specimen. Figure 6 displays two sets of 10mm thick composite laminates that were manufactured by the author and tested using an Instron Dynatup 9250HV drop tower. Both sets of laminates were manufactured with a layup sequence of [+45/-45/0/0/90/0/0/+45/-45/0]s, which was selected to be representative of a tidal turbine blade skin. Set A was manufactured from Proset 117/M2010 epoxy resin and 600gm unidirectional Advantex glass fibre (FGE708), whilst set B was manufactured from Elium 180 resin and 600gsm unidirectional Chomorat glass fibre (BT640). Three specimens were tested in each set, with each specimen being exposed to a single 20J and 40J impact. Further details of these tests (including the force-time history for each impact specimen) is provided in Appendix A.5. The difference in visible impact damage (Figure 6) and impact response (Appendix A.5) between the two sets of specimens clearly demonstrates the importance of material selection for these applications.

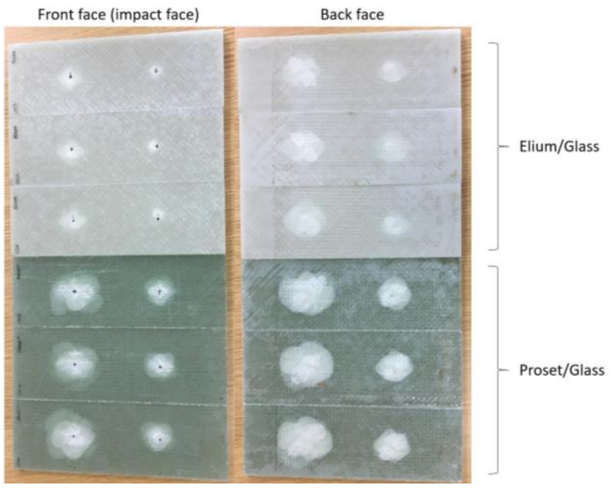


Figure 6: Impact test specimens for two composite laminates

It is important to test laminates with thicknesses representative of real structures, as impact damage is dependent on laminate thickness (Sutherland, 2005). Thicker laminates have been shown to suffer from delamination at lower impact loads than thinner laminates. Some thick laminates can take years to fully saturate in conditioning tanks, meaning it can be difficult, and often unfeasible, to fit such test programs into a typical design project. Moisture uptake can result in a softening of the composite matrix over time, predominantly due to plasticisation. This effect has been shown to affect the impact response of composite laminates (Imielinska, 2004). It is also important to consider the post-impact strength of a laminate. Local impact damage in the form of fibre breakage and delamination can significantly reduce the in-plane properties of a composite laminate, especially when combined with other environmental factors. Compression after impact tests can be used to investigate such effects. ASTM D7137 provides a detailed explanation of this method. Investigations into the compression after impact behaviour for wet and dry laminates clearly indicate a reduction in compressive strength due to moisture uptake in addition to impact damage (Sala, 2000) (Imielinska, 2004).

2.5.4 Fatigue testing of conditioned specimens

Marine structures such as tidal turbine blades must be designed to withstand harsh fatigue loading. However, complete fatigue testing of conditioned laminates is both time consuming and costly, and so is often limited in industry to a few select laminates. It is therefore difficult for companies to compare the fatigue performance of a wide range of composite laminates, and for this reason, cheaper, quicker static tests are often used instead for the purposes of material selection.

The cost to conduct fatigue tests is proportional to the number of cycles performed. Careful consideration is therefore required when planning fatigue testing. In some cases, it may be sufficient to conduct fatigue tests with a low number of cycles and estimate strength for higher cycles via extrapolation (Echtermeyer, 2018). However, experimental proof of the fatigue performance of a material will help to reduce project risk and is often crucial for fatigue-driven designs.

As with static mechanical properties, moisture absorption into the laminate acts to reduce the fatigue strength of the composite structure. This can be shown graphically as a drop in the S-N curve compared to dry coupons. The degradation of tensile fatigue strength has been investigated for an epoxy/E-glass laminate (Jaksic, 2018). This work has demonstrated that the fatigue degradation of saturated laminates, ranging from 8-25% compared to dry, is dependent on the number of loading cycles. Therefore, the gradient of the S-N curve can also vary depending on material. Sun and Dawson also found this to be true for other glass and carbon epoxy laminates (Sun, 2013). This is an important consideration for the designer, as knockdown in fatigue strength can vary with both application and material. This highlights the need for full fatigue testing of both dry and saturated coupons for high performance design projects. Such test programs are both costly and time consuming as previously discussed.

2.5.5 Further testing of conditioned specimens

The ability of a material to resist constant load over an extended duration is also of significant interest to designers. Creep and stress rupture tests can be used to investigate long-term damage and potential failure due to the application of a constant load significantly lower than the ultimate tensile strength.

It may also be desirable to combine an applied stress with environmental effects to further investigate the limits of the chosen material, generally referred to as stress-ageing. For example, one may wish to investigate the effects of a constant tensile stress applied to a specimen submerged in sea water, or for deep sea applications to condition specimens under a constant, elevated pressure. Alternatively, a worst-case scenario may be investigated where a hot/wet conditioned specimen is subject to compression-after-impact or creep/fatigue loading. These tests are thought to be more accurate as they can account for coupling effects between multiple conditions that may or may not be apparent to the designer and can be difficult to predict analytically. Stress corrosion cracking of glass fibres is one such effect that is commonly investigated, and heavily dependent on the external environment (Maxwell, 2005). Kennedy et al. describe a test procedure in which vinyl ester/E-glass specimens are exposed to 10,000 fatigue cycles between 0.8kN and 8kN prior to wet and dry stress-ageing for 21 months (Kennedy, 2016). These loads were selected to generate cracking in the 90° plies, simulating expected in-service damage of a tidal turbine blade.

Larger, thicker coupons are more representative of real-world structures, and give a better indication of performance for designs incorporating thick laminates. Research has suggested a scaling effect is present whereby the mechanical properties are dependent on specimen dimensions (Wisnom, 2009). This is therefore another factor that should be taken into account when designing durability tests.

2.6 Potential Modifications to Current Seawater Conditioning Techniques

Current techniques for determining seawater degradation of composite laminates can be time consuming and costly due to long conditioning times and the need for extensive mechanical testing. Whilst there is currently no reliable alternative procedure for generating accurate laminate data for structural designs, it may be possible to further accelerate the current procedure by raising the conditioning temperature to reduce product development time and cost. Furthermore, this process may also be simplified for the purposes of initial material down-selection to enable rapid selection of the most suitable materials early in the design process. To determine whether these modifications would be applicable to the selected composite laminates, further investigations were conducted by the author to understand how conditioning temperature affects moisture absorption and laminate mechanical properties.

2.6.1 Further Accelerated Seawater Conditioning Procedures

Increasing the conditioning temperature may be an option for further accelerating current conditioning techniques. The wet Tg of typical composite laminates utilised at Airborne UK for marine applications is estimated to lie between 60-80 °C. It is therefore suggested that increasing the conditioning temperature from 45°C to 55°C could be a suitable way to accelerate the conditioning process further. However, it is important to investigate the potential impact this could have on laminate moisture absorption and mechanical properties.

2.6.1.1 Effect of Raising Conditioning Temperature on Moisture Absorption

Samples of glass/epoxy laminates A and B were conditioned in sea water at 25°C, 35°C, 45°C, and 55°C until saturation. The weight gain due to moisture absorption was recorded periodically during this time. Figure 7 and Figure 8 show this data for glass/epoxy laminates A and B, respectively. This data indicates that raising the conditioning temperature from 45°C to 55°C accelerates the initial moisture uptake, reducing the saturation time from 73 days to 52 days for laminate A and 153 days to 60 days for laminate B. The higher temperature raises the saturation level by approximately 0.1% total weight gain for both laminates. It is evident that the weight gain at 55°C follows a similar trend to that at 45°C. Both sets of data exhibit close agreement with Fickian moisture absorption. Therefore, raising the conditioning temperature by 10°C does not appear to change the mechanism by which moisture is absorbed into the laminate. Samples of all the other laminates were conditioned in sea water at 45°C and 55°C and showed similar moisture absorption trends to those seen with glass/epoxy laminates A and B. From the perspective of moisture absorption, raising the conditioning temperature to 55°C appears to be applicable for these laminates.

Figure 7 and Figure 8 also show moisture uptake into glass/epoxy laminates A and B at lower temperatures (25°C and 35°C) that are closer to representative service temperatures (~10°C). The rates of moisture uptake and saturation levels are significantly slower at these temperatures.

2.6.1.2 Effect of Raising Conditioning Temperature on Mechanical Properties

Raising the conditioning temperature may also impact the measured mechanical properties of the laminate, and thus the validity of the product structural design. Figure 9 and Figure 10 show the knockdowns (wet/dry) in ILSS and flexural strength due to conditioning at 45°C and 55°C compared to unaged specimens. It is evident that the slight increase in saturation level observed for specimens conditioned at 55°C results in a further reduction in mechanical properties of between 1 and 10% depending on the material.

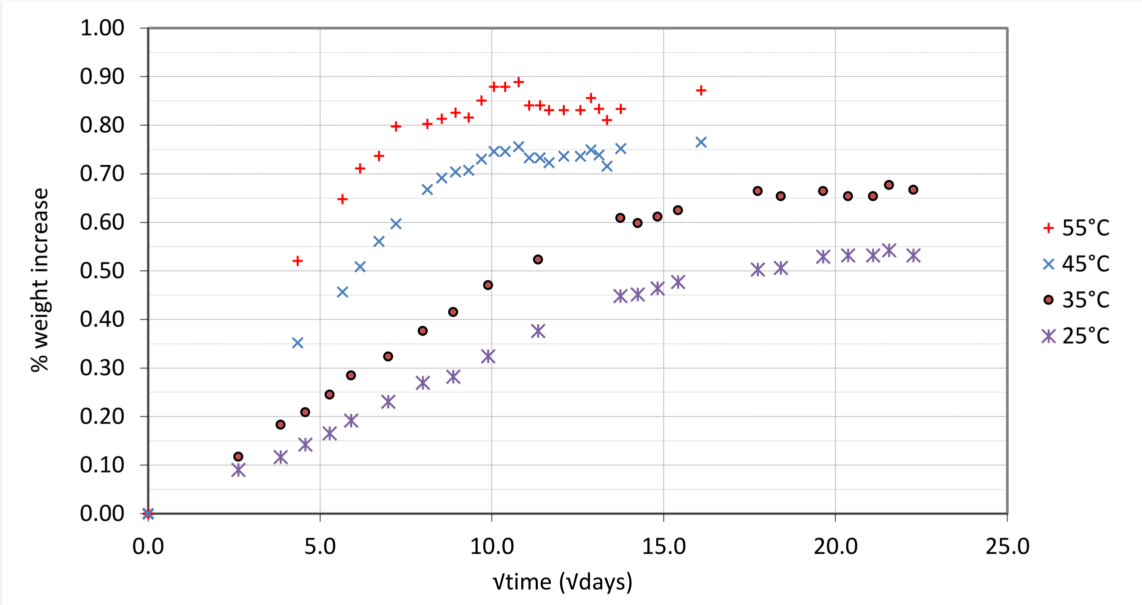


Figure 7: Comparison of weight gain due to moisture absorption at different temperatures for glass/epoxy laminate A

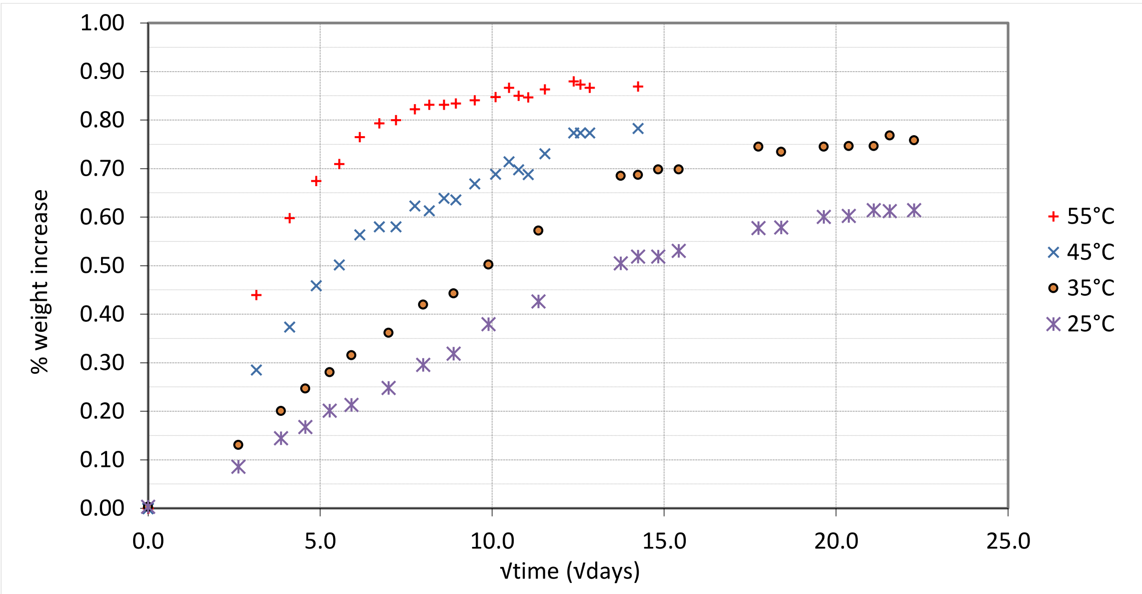


Figure 8: Comparison of weight gain due to moisture absorption at different temperatures for glass/epoxy laminate B

The results in Figure 9 and Figure 10 suggest that conditioning composite laminates in sea water at 55°C produces generally conservative results compared to lower temperatures. The effect of higher temperatures varies among the materials investigated. For most specimens, the difference in strength between the two temperatures is small: around 5%. However, some specimens experience a reduction in strength of approximately 10% due to the higher conditioning temperature. Furthermore, there are two examples where conditioning at 45°C results in a greater strength knockdown compared to 55°C (carbon/epoxy laminate C ILSS and glass/epoxy laminate C flexural). By raising the conditioning temperature to 55°C, the results indicate, on average, lower material strengths, although the two outliers suggest that the resultant impact on laminate strength is variable.

Figure 9 also displays the ILSS knockdown for glass/epoxy laminates A and B when conditioned in seawater at 25 and 35°C until saturation. A general trend can be seen in which the ILSS knockdown reduces with lower conditioning temperatures. Glass/epoxy laminate A at 35°C is the exception to this trend, highlighting that, as with the previous outliers at 45 and 55°C, there is no simple trend that describes the relationship between conditioning temperature and strength knockdown for all material samples. Differences in resin and fibre chemistry and potential variations in material batches, manufacturing processes, coupon preparation, and mechanical testing lead to a complex material degradation process that is very difficult to accurately predict.

The general trend of higher strength knockdowns at higher conditioning temperatures indicates that there is a trade-off between conditioning speed and the conservative nature of the results. This may allow designers to obtain material degradation data more rapidly at the expense of slightly less optimised designs. This would not have a detrimental effect on the longevity or safety of the structure as the strength knockdowns would be more conservative with faster conditioning procedures. However, the presence of outliers in the data indicates that this trend is not true for all specimens, and so further work is suggested to investigate a wider range of laminates and identify which materials this accelerated procedure is suitable for.

Previous studies have shown that increasing the conditioning temperature from 20°C to 50°C has a detrimental effect on shear modulus and strength of polyester, vinyl ester and epoxy laminates (Davies, 2008). In this study the specimens were conditioned for approximately 14 months, and the results indicate that the effect of raised temperature is dependent on resin selection.

The higher degree of conservatism in design data generated from these further accelerated conditioning tests may not be acceptable for some commercial applications. To account for this, it may be possible to use theoretical models to predict the effect of conditioning temperature on mechanical performance, thereby allowing the data to be corrected to account for conservatism in experimental results. Such models may also be used to predict the saturation time of specimens, allowing organisations to better plan and budget testing procedures. This approach is discussed in Section 2.7.

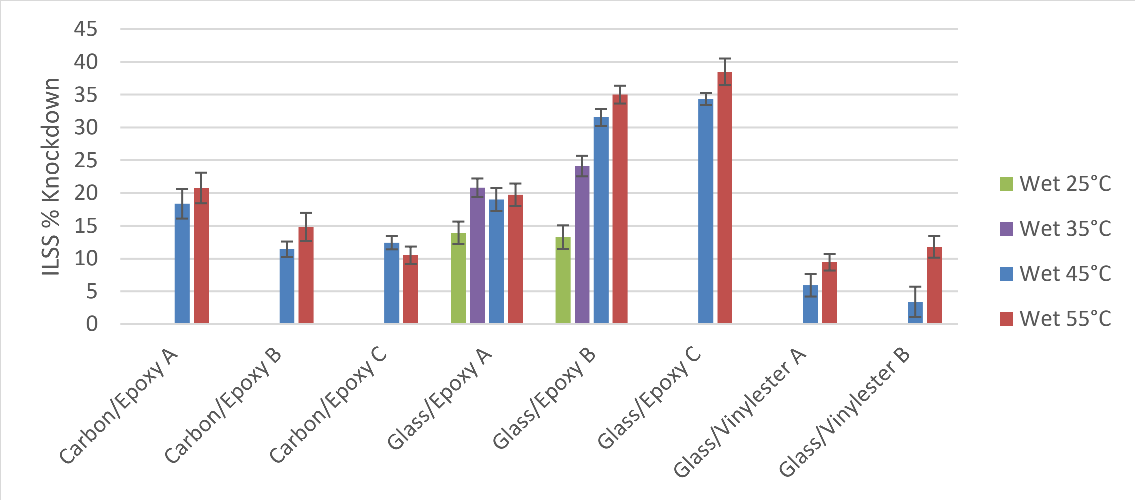


Figure 9: Comparison of ILSS knockdown of typical marine laminates in seawater at different temperatures

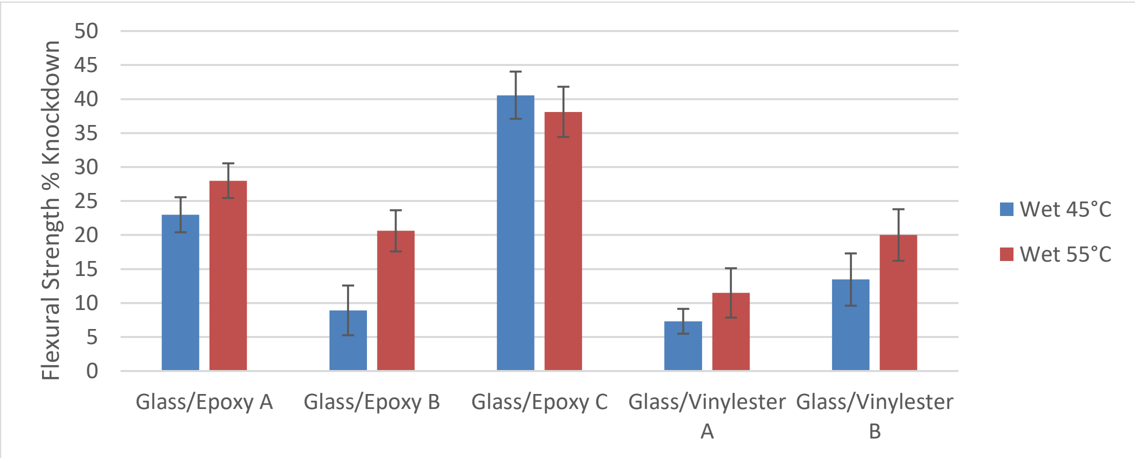


Figure 10: Comparison of flexural strength knockdown of typical marine laminates conditioned at 45°C and 55°C

2.6.2 Simplified Conditioning Procedures for Initial Material Selection

Mechanically testing laminate specimens requires specialised test rigs and trained personnel, which may not be readily available at every company. These tests can be outsourced to dedicated testing facilities; however, this can be expensive and time consuming and is generally not commercially viable for the purposes of initial material selection. Instead, the relationship between moisture absorption and reduction in mechanical properties may be a more cost-effective approach to determine the suitability of certain laminates during the material selection phase. Shen and Springer have demonstrated that the tensile strength and elastic modulus of a specific composite laminate reduces with increased moisture content (Shen & Springer, 1976) (Shen & Springer, 1977). Figure 11 displays the reduction in ILSS against moisture absorption at saturation for glass/epoxy laminates A, B, and C and glass/vinyl ester laminates A and B. The data indicates that for this group of materials the reduction in ILSS is proportional to the level of moisture absorbed. This trend agrees with findings from previous studies of similar materials (Dawson, 2016). The data in Figure 12 also indicates a similar trend for the knockdown in flexural strength of these same materials.

Whilst these relationships between strength knockdown and moisture uptake are interesting and potentially useful for material selection, it is important to note that a broader test program would be required to understand whether these trends are valid for a wider range of composite materials beyond those tested in this study. Nevertheless, the presence of these strong trends for the epoxy and vinyl ester glass fibre reinforced composites tested in this study indicates that measurements of moisture absorption alone may be a satisfactory approach for rapidly down selecting some resins and/or composite laminates. The presence of two outliers in the flexural strength trend in Figure 12 ((0.32, 20.01) and (0.77, 8.92)) indicate that down-selection of materials may be more effectively conducted using ILSS data.

As outlined in Section 2.2.3, the moisture ageing of composite laminates can be a complex process consisting of multiple interconnected mechanisms such as moisture absorption, chemical reactions between the water and resin (hydrolysis) and propagation of physical damage (microcracking). Accurate prediction of the ageing behaviour of specific composite laminates is therefore very difficult. The use of more generic trends, such as those presented in Figure 11 and Figure 12, may be a cost-effective approach for the initial down-selection of laminates that experience similar ageing mechanisms. Furthermore, predicting moisture absorption using numerical methods is much simpler than predicting material degradation. Therefore, these trends could be combined with numerical methods to rapidly identify a set of suitable laminates. This approach is discussed in the next section.

It is suggested that additional testing be conducted on a wider range of laminates and temperatures to determine if this trend is valid for all materials relevant to the case studies featured in this thesis. This would require collaboration between numerous companies, research organisations and academic institutions to generate such a wide pool of data. Collation of this information into a publicly available global database would allow industry to use existing data and data trends (where appropriate) to rapidly select the most appropriate materials for a given application. It is also important to note that there are examples in literature of composite materials that do not agree with the trends presented in Figure 11 and Figure 12 (Wang, Y., et al., 2021) (Ahamad, M.A.A., et al., 2018) (Mingyang, C., et al., 2020) (Sang, L., et al., 2019). As a result, it is suggested that data trends such as these should be used with a high degree of caution, and only for similar types of materials and top-level down-selection activities. It should be noted that this alternative approach would not replace the need for extensive material testing to generate suitable design data for specific/chosen materials.

It may also be interesting to expand this study to decouple the ageing effects of sea water submersion and temperature by conditioning an additional set of coupons in a dry oven environment for an extended duration. This may help engineers better understand how representative current conditioning procedures are. This additional investigation is suggested as future work. No further experimental studies related to composites marine durability were conducted as part of this durability study due to time and resource limitations. After these experiments were conducted, the author's attention was diverted towards managing and conducting research activities related to the manufacturing challenges of large composite marine structures. It is for this reason that the durability study in this chapter is generally limited to the initial material selection stage.

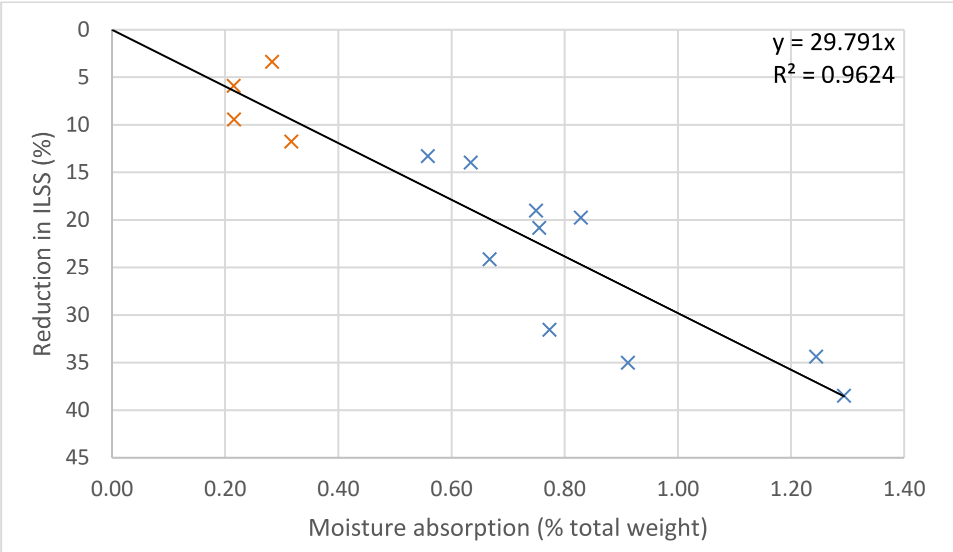


Figure 11: Relationship between ILSS knockdown and moisture absorption for glass/epoxy (blue) and glass/vinyl ester (orange) laminates

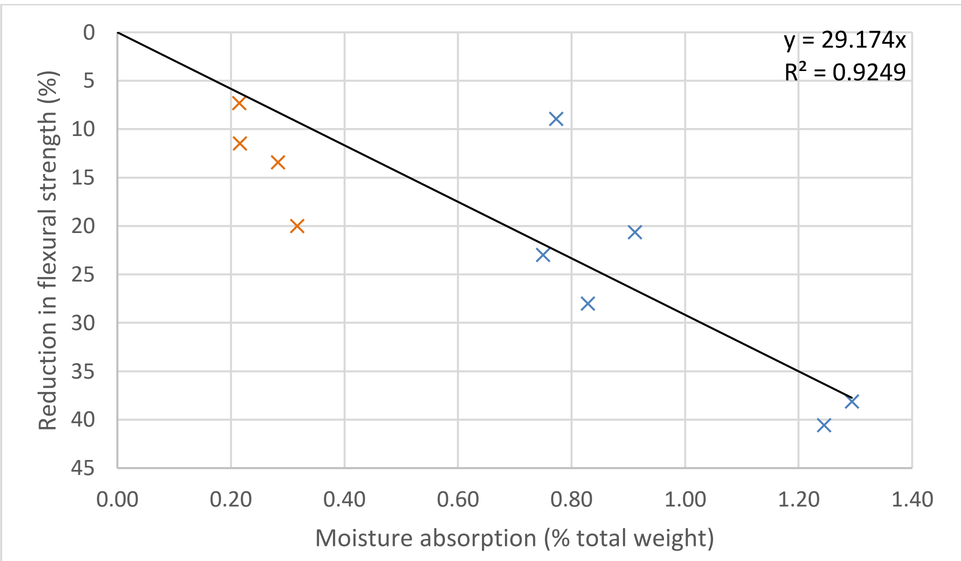


Figure 12: Relationship between flexural strength knockdown and moisture absorption for glass/epoxy (blue) and glass/vinyl ester (orange) laminates

2.7 Modelling of accelerated moisture absorption

The complexity of the moisture degradation process combined with potential variations in laminate properties (due to differences in material batches and manufacturing processes) means that it is very difficult to generate accurate predictions of durability using numerical methods. However, these models may be useful to support experimental data, potentially enabling accelerated and reduced physical testing. This section describes a basic model for predicting the moisture uptake within a composite laminate that could be applied with the experimental data gathered in the previous section to aid the material down-selection process in industry.

2.7.1 Fickian diffusion

It was previously discussed that for flat composite plates with relatively small thicknesses compared to length and width, diffusion is dominant in the thickness direction, and therefore one-dimensional. If one also assumes steady-state diffusion, then the simple model of Fick's law can be applied to describe moisture diffusion through a composite laminate (Colin, 2014), Equation (1).

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} \quad (1)$$

Where C is the local water concentration, z is the depth in the thickness direction and D is diffusivity.

The analytical solution to this equation is given below, Equation (2) (Chilali, Assarar et al. 2017)

$$\frac{M_t}{M_\infty} = 1 - \left(\frac{8}{\pi^2}\right)^3 \sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty} \frac{exp\left(-\pi^2 t\left(D_1\left(\frac{2i+1}{L}\right)^2 + D_2\left(\frac{2j+1}{w}\right)^2 + D_3\left(\frac{2k+1}{h}\right)^2\right)\right)}{((2i+1)(2j+1)(2k+1))^2} \quad (2)$$

Where L, w and h are length, width and thickness respectively, $M_{infinity}$ = Moisture uptake at saturation, and Mt, the periodic weight gain, is expressed in Equation (3).

$$M_t = \frac{W_t - W_0}{W_0} \quad (3)$$

Where W_t = specimen weight at time, t and W_0 = dry specimen weight.

Three separate diffusivity values (D) are present in Equation (2), one for each primary direction in the orthotropic composite material. These parameters must be found via separate absorption tests in each of the primary directions. As diffusion through the thickness is dominant for a flat composite plate with relatively low thickness, it is sufficient for industrial purposes to assume a single diffusivity. The equation then simplifies to the form in Equation (4) (Naceri, 2009):

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2}\sum_{k=0}^{\infty} \frac{exp\left(-(2k+1)^2\pi^2\frac{Dt}{h^2}\right)}{(2k+1)^2} \quad (4)$$

The first 6 terms (j=1 to 6) of Equation (4) will give sufficient accuracy for most industrial purposes. Assuming a semi-infinite plate with low water concentration on the back surface, Equation (4) can be simplified further and rearranged to give the diffusivity, D, in terms of the initial linear rate of moisture uptake, moisture saturation level and specimen thickness (Shen & Springer, 1975), Equation (5).

$$D = \pi \left(\frac{h}{4M_\infty}\right)^2 \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \quad (5)$$

The calculated value for D can then be inserted into Equation (4) to calculate the predicted periodic weight gain according to Fick's law. Therefore, the periodic weight gain of a composite laminate can be predicted with only three variable inputs: Thickness, initial linear rate of moisture uptake, and moisture uptake at saturation. This greatly simplifies the analysis and allows for a fast, theoretical prediction of the weight gain plot.

2.7.2 Effect of temperature on diffusivity

The previous analysis is independent of temperature. One can predict the effect of temperature on moisture absorption by assuming that diffusivity varies with temperature following the Arhhenius relationship in Equation (6).

$$D = D_0 \, exp\left(-\frac{E_D}{RT}\right) \quad (6)$$

Where E_D is the activation energy of water diffusion, R is the universal gas constant, T is temperature in Kelvin and D_0 is a constant. Using this equation, one assumes that diffusivity is independent of water activity.

Both E_D and D_0 can be found by reducing Equation (6) to a linear form; Equation (7).

$$ln(D) = \frac{-E_D}{RT} + ln(D_0) \quad (7)$$

Both E_D and D_0 can then be found by plotting ln(D) vs 1/T. To do this, a minimum two values of D for the same laminate at two different temperatures are required. The accuracy of this method improves with the number of temperatures investigated (Starkova, 2013) (Deroine, 2014).

These values can then be inserted into Equation (6) to estimate the diffusivity at different temperatures, which can then be inserted into Equation (4) to estimate the periodic weight gain at different temperatures. Alternatively, one can use E_D values from other literature sources (Colin, 2014), but it is important to note that this method is only valid for temperatures below the Tg of the laminate in question.

2.7.3 Effect of temperature on saturation level

Research has shown that the maximum moisture content diffused into a composite is dependent on temperature (Davies, 2008), and data presented in Figure 7 supports this. Predictive tools should therefore account for this effect. A simple approach is to assume that water concentration follows Henry's Law, Equation (8) (Merdas, 2001). The use of this equation is based upon the assumptions that water concentration (weight gain) remains low (less than 7%) and that the polymer matrix does not change state.

$$C = Sp \tag{8}$$

Where C = equilibrium water concentration (equivalent to Minf), S = coefficient of solubility, p = water vapour pressure.

One can assume that S and p vary with temperature according to an Arrhenius law. The latter only follows this law between 20°C and 100°C (Merdas, 2001). These two relationships can be combined with Equation (8) to form the following Arrhenius equation, Equation (9) (Merdas, 2001):

$$C = C_0 \, exp\left(\frac{-H_C}{RT}\right) \tag{9}$$

Equation (9) can be made into linear form, and the values H_c and C_0 found using the same method as described previously. The Arrhenius equation can then be used to calculate the predicted equilibrium water concentration (or saturated moisture level).

2.7.4 Application of the model

Figure 13 displays the weight gain plots at different conditioning temperatures for Glass/Epoxy laminate B. Fickian absorption curves are fitted to the experimental data measured at 45°C and 55°C using the methodology outlined in Section 2.7.1. The data shows that the process of moisture absorption into the glass/epoxy specimens can be described well by the simplified analysis based upon Fick's law. Indeed, in its simplest form this method can be used in industry to check whether experimental data follows a Fickian absorption trend, and therefore gain a basic understanding of the mechanisms by which moisture is absorbed into the specimen.

The assumed Arrhenius relationships outlined in Sections 2.7.2 and 2.7.3 are applied to create theoretical predictions of the Fickian absorption curves one would expect at 25°C and 35°C. These predictions match closely with the experimental data, as shown in Figure 13. As a result, one can be confident that the Arrhenius relationships that relate conditioning temperature to diffusivity and moisture saturation level are valid for the materials in this study. It is important to note that this may not be true of all composite materials.

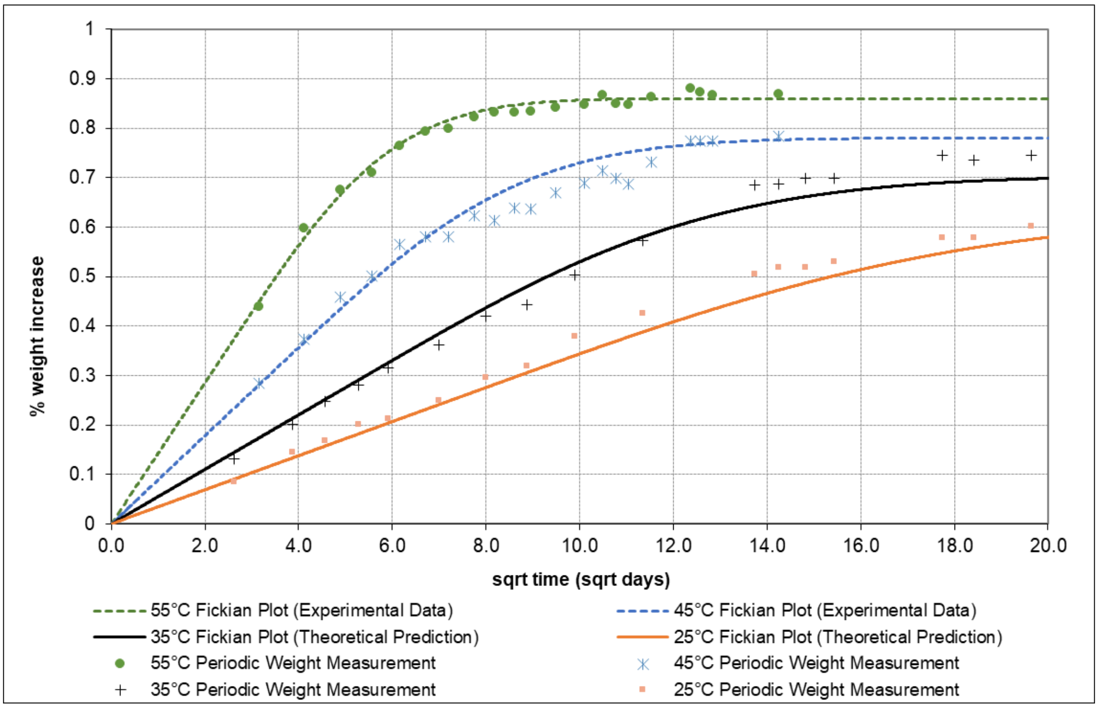


Figure 13: Fickian prediction of weight gain of a glass/epoxy composite laminate due to moisture absorption and the effect of temperature variation.

Figure 13 illustrates how the Fickian model can be used to estimate the effect of conditioning at other temperatures once calibrated using experimental data. In future, it may be possible to combine this method with the relationship between knockdown in strength and moisture absorption (Figure 11) to predict the knockdown in strength at various, untested temperatures. This would allow designers to conduct accelerated conditioning procedures at elevated temperatures, then correct the observed knockdowns in laminate strength to produce design data representative of in-service temperatures.

This analysis technique can also predict the time taken for a specimen to fully saturate but is limited by the need for some existing experimental data to which the Fickian curve can be fitted. Therefore, a prediction of saturation time can only be made once the specimen conditioning is underway. However, this limited information can help companies predict project durations to greater accuracy. The accuracy of this prediction may be improved by also considering the behaviour of similar laminates that have previously been tested. Purnell et al. also present a model that may be used to predict the duration of accelerated ageing required to represent equivalent in-service lifetimes (Purnell, 2008).

Since thickness is a variable in the Fickian analysis, it is possible to predict the rate of moisture absorption at different thicknesses. Figure 14 displays the predicted weight gain curve for a specimen of 1mm thickness at 45°C, compared to the actual specimen thickness of 2.7mm. Predicting the effect of thickness in this way assumes that the diffusivity is unchanged. This assumption would only be valid for thin plates where diffusion through the thickness is dominant.

Limiting moisture absorption to only the through-thickness direction during conditioning allows measurement of the diffusivity in this direction. A combination of this test data and the above model can then be used to predict the long-term moisture penetration in composite structures operating in a typical marine environment. This can indicate to the designer what proportion of the laminate will experience moisture degradation over the design life, and therefore help to avoid over-conservative design safety factors being applied.

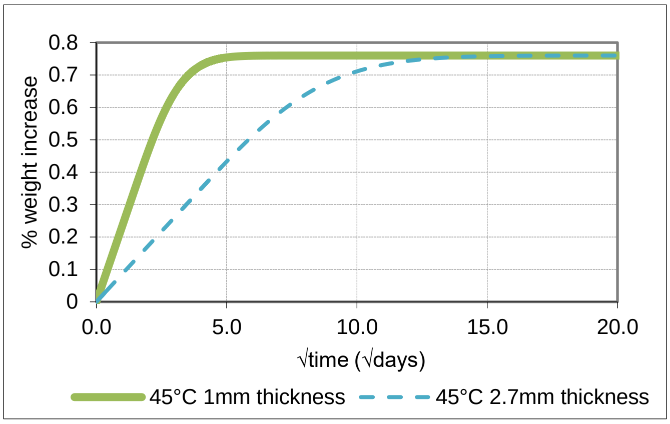


Figure 14: Fickian prediction of weight gain of a glass/epoxy composite laminate due to moisture absorption and the effect of specimen thickness variation.

2.7.5 Limitations of the model and potential improvements

The simplicity of the Fickian diffusion model presented allows the prediction of moisture absorption over time for a wide range of composite laminates. Although a number of more advanced models are available to predict the behaviour of specific laminates, as one focuses on more detailed diffusion behaviour, the range of materials to which these models can be applied decreases. This limits their application but may be of interest to companies who utilise a very small number of specific materials.

Depending on the level of accuracy required, the Fickian modelling technique could be extended further to include all three diffusivities, making it applicable to specimens of other shapes and dimensions. Other absorption models may also be used when specimens exhibit non-Fickian behaviour. Case II, sigmoidal and two-stage absorption models can all be used to match experimental data more closely.

It should be noted that the above models are limited in their application as they map basic analytical models to experimental data; one must have the experimental data in order to apply the models. However, they give potential to significantly reduce the amount of physical test data required and therefore, the time and cost involved in its acquisition. Whilst the data presented both here and in other sources show general trends for moisture absorption and mechanical degradation that may be used for top-level material selection, further research is needed to refine the accuracy of the predictive models.

This model is presented as a useful generic tool that can be used in industry to gain a simplified understanding and prediction of the initial moisture absorption response of typical marine composite laminates for the purposes of rapid material down-selection. Further refinements and more detailed modelling approaches (including implementation of alternative absorption curves) are left for future work. Due to the limited time and resources available to conduct this study, it was decided that a simpler approach encompassing a wide range of composite laminates would be the most appropriate route.

It is also important to note that due to the limited scope of this investigation, this approach is only appropriate for the initial material selection phase. Again, due to limited time and resources, it was not possible to expand this study to investigate cost effective methodologies for reducing the cost of generating detailed durability design data. Currently, there is no alternative to extensive material testing and accelerated conditioning procedures. The following section outlines some areas of research that are currently being conducted to address this issue.

2.8 Constituent-level predictive methods

The majority of research that has been conducted to this date considers the moisture degradation effect at a laminate level. As a result, accurate predictions of long-term durability are only valid for specific laminates that have been previously tested, which can be costly and time-consuming. For such tools to be applicable to industry, they must be cost-effective and valid for a wider range of composite materials.

Modelling of ageing at a constituent level has been proposed as an alternative to laminate-level predictions (Echtermeyer, 2018). Predicting laminate mechanical properties from constituent data is commonly used by both academia and industry in the form of classical laminate analysis (CLA). It is thought that combining CLA with constituent-level degradation predictions will provide a much greater level of flexibility during product design, as well as greatly reducing the level of physical testing required.

Such models will also require accurate knowledge of the chemistry and formulation of each constituent part, and it can be difficult to persuade manufacturers to give away this information. A laminate, in its simplest form, is a combination of three unique constituents: fibre, resin and sizing. It is the combination of all three constituents that determines the laminate properties. The quality of the bond between all three components is determined by the chemical and physical properties of each as well as manufacturing parameters.

Of course, combining the ageing effects of multiple constituents is a complex task, especially when one considers the combined effects of multiple environments such as moisture, temperature and chemical attack in addition to applied stresses. Indeed, the ageing behaviour of each constituent may also be dependent on the behaviour of the other constituents. For example, it has previously been discussed how resin acts as a protective barrier to shield glass fibres from moisture exposure. Complex analytical models will be required to predict the combined ageing of constituents at a laminate level.

Molecular dynamic simulations, which concerns the movement and interactions at the atomic and molecular scale to determine macroscopic material properties, is one approach that may be used to investigate moisture absorption behaviour within composite materials. This approach has been applied in literature to predict moisture absorption through various types of materials. For example, Stoffels et al. used molecular dynamic simulations to investigate the effect of water absorption on the glass fibre/epoxy interface of a specific laminate and found that simulation results of saturation limit matched fairly closely with experimental data (Stoffels, M. et al., 2019). Other studies have successfully used molecular dynamic simulations to predict moisture diffusion behaviour (Pandiyan, S., et al., 2015) and mechanical properties of crosslinked epoxy resin (Okabe, T., et al., 2016). Whilst this appears to be a promising approach, it appears further work is required to investigate a wider range of composite materials and incorporate long-term moisture degradation effects beyond initial diffusion. There is also a need to validate simulation results with experimental data due to the complex nature of the simulations, and it may take years to obtain relevant data for in-service moisture degradation of composite laminates. Furthermore, the technical understanding and specialised measuring apparatus that is required to conduct these simulations would likely not be available in a typical composites design and manufacturing company. Further development is therefore required in this field before this approach can be applied reliably in industry.

Development of these constituent level models will be critical for lowering the cost barrier for composites in many large-scale marine applications. If such models can predict the complex and coupled absorption and degradation mechanisms of composite laminates, it may be possible to severely limit the amount of long-term durability testing required in industry. Instead, simple and cost-effective dry, static tests may be conducted alongside detailed chemical analysis of the constituent materials to obtain baseline laminate properties, from which a wide range of potential cases could be predicted and analysed (including service life, temperature and humidity/environment conditions and potential manufacturing defects). These predictions could be validated via a limited number of conditioning tests. This “building block” approach would significantly increase the quantity of design data available to the engineer and enable a far more effective method of selecting appropriate laminates for specific applications.

2.9 Conclusions and future work

Predicting the long-term durability of composite laminates is a complex and time-consuming procedure; however, an accurate understanding of how specific laminates degrade in a marine environment is critical for ensuring adequate structural life and safety. The research presented in this chapter indicates that dry and wet material properties can vary significantly between materials marketed for the same purpose. Furthermore, manufacturing variations can exaggerate this effect. It is therefore important that composite manufacturers aiming to use such materials for marine applications perform extensive durability testing to better understand their properties and limitations. However, current accelerated conditioning practices are costly and time consuming, resulting in longer project durations and increased project risk. Modelling techniques of various complexities may be used alongside testing programs to give more accurate predictions of conditioning duration. Currently, the most reliable method for obtaining long-term durability data is through physical testing.

The investigations conducted in this chapter have identified a trend across a range of marine composite laminates in which higher conditioning temperatures result in greater laminate strength knockdowns. This indicates that faster conditioning procedures may be applied at the expense of more conservative designs. The presence of outliers in the data suggests that this is not always a robust approach, and further work is required to investigate the applicability of this method over a wider range of composite laminates. The data also highlights a trend between moisture absorption at saturation and strength knockdown, with laminates that absorb greater quantities of moisture experiencing on average greater knockdowns in strength. Whilst this appears to be a strong trend for the materials tested, it should not be taken as a general trend for all composite laminates, as literature has demonstrated that there are materials which do not follow this trend. Even so, it may be possible to apply this trend with numerical predictive tools to simplify and accelerate the material down-selection of laminates manufactured using similar constituent materials or processes. This may be of particular benefit for smaller companies that focus on specific types of composite laminates.

There is still further work remaining to develop accurate accelerated composite ageing prediction methods across a range of different material types. Each unique laminate combination of fibre, resin and sizing must be extensively tested, the results of which are only applicable to that certain combination. Whilst improvements can be made to current processes in the form of accelerated conditioning and predictive methods using general trends, extensive testing cannot yet be avoided. Whilst constituent level models may allow further reduction in physical testing, this approach is at a very early stage. The development of such tools will be a complex process, requiring input from material suppliers, product designers and manufacturers. Both laminate level and constituent level models could play a role in reducing the engineering cost of composite structures, the former for material selection, and the latter for in-depth structural design.

Any analytical method that aims to replace physical testing must be proven to be reliable over a wide range of materials. In the future it may be possible to predict the effects of long-term submersion in sea water on a wide range of composite materials with much greater accuracy. This knowledge can then be used to improve the efficiency of structural designs and reduce project duration and cost. In the meantime, selecting a few “standard composite laminates” for large marine applications may be a beneficial way to focus and accelerate global understanding of long-term composites durability for specific applications. For example, 3 standard reinforcement and resin types could be defined for use in large marine structures, resulting in 9 standard composite laminates that could be used for these applications (some classification bodies such as Lloyd’s Register define approved resins and reinforcements for marine applications, although approved laminates do not appear to be defined). Academia and industry could then generate an extensive pool of data for these materials, which could be used throughout the global marine industry to simplify the design and certification processes for large marine structures and provide a greater level of confidence in long-term structural integrity. This approach would require cooperation between research, manufacturing, and certification organisations across the globe, and so commercial and political factors would also need to be considered. Multi-national research projects such as RAMSSES and FIBRESHIP could help to initiate this approach. Whilst standardised laminates may help to accelerate global research efforts in this area, this approach may limit innovation in composite materials, impacting the commercial competitiveness against steels. and restricting the adoption of more environmentally friendly constituent materials such as bio resins, natural fibres, and recyclable resins such as Elium.

3 LARGE COMPOSITE MARINE STRUCTURES – A SHIP HULL CASE STUDY

3.1 Introduction

The previous chapters have explored market analysis and material selection for general marine composite structures. The following chapters will build upon this work and investigate product design and manufacture, with particular focus on the development of a manufacturing process for large composite marine structures. In order to develop a detailed manufacturing process, this work must be focused on a specific case study. The composite ship hull was selected as the primary focus of this work for the following reasons:

- Time and resource limitations meant that it was not possible to conduct this manufacturing process development work for both case studies.
- The composite ship hull was identified as being the more challenging structure to manufacture of the two case studies selected.
- This manufacturing research was conducted as part of a broader research project (RAMSSES), which focuses on innovation in the European shipbuilding industry.

Despite the focus on the ship hull case study, it is important to note that many of the challenges addressed in this work are also relevant to other large composite marine structures (including tidal turbine blades).

The development of a suitable manufacturing process is a critical step in the product development cycle. This is even more true for composite products due to the complex nature of the materials and manufacturing processes. Unlike with metals, there are no standard “pre-made” fibre-reinforced composite material grades that can be used to produce large marine structures. The combination of constituent fibres, resin and other elements must be processed on the manufacturing line to generate a usable structural material. Therefore, both the material properties and structural properties are dependent on the manufacturing process, so process variation can have a significant impact on structural properties and product performance. Additional novel features of the selected ship hull case study, such as the scale (50m+) and thickness (200mm+), further add to the complexity of the manufacturing process. As outlined in Chapter 1, there are currently no examples of such structures being commercially manufactured. As a result, there are no standardised manufacturing processes currently used in industry, leading to significant product development costs. There are numerous composite manufacturing processes to choose from, each with their own advantages and disadvantages depending upon the product in question.

The manufacturing process also represents a significant portion of the overall product cost. Efficient design of the product and process early in the development cycle can translate into great cost reductions during large-scale production. This can be achieved by implementing a concept known as "Design for Manufacture": the iteration between product design and manufacture that ensures the production process is as efficient and affordable as possible. Suitable manufacturing design also allows the designer to fully exploit the material properties, thereby increasing the structural efficiency and performance of the product. Incorrect process design can lead to defects and features that weaken the product.

The remaining 4 chapters of this thesis focus on the development of a commercial manufacturing process for a large ship structure. The first steps of this work are the selection of a suitable case study and manufacturing process.

3.2 The RAMSSES Project

The RAMSSES project (Realisation and Demonstration of Advanced Material Solutions for Sustainable and Efficient Ships) is a Horizon 2020 research project which aims to improve the sustainability and operational efficiency of European-made ships. This shall be achieved by replacing conventional steels within various ship structures and components with advanced materials such as high-strength metal alloys and polymer-based composites. In doing this, the structural weight (and hence fuel consumption) of various types of vessels may be reduced, whilst the durability of these structures (and hence operational lifespan) may be increased. The primary goal of this project is to demonstrate a 30% reduction in maintenance and life-cycle costs through the implementation of advanced materials compared to conventional materials and processes (this demonstration is beyond the scope of the work presented in this thesis). The RAMSSES project is conducted as a collaborative research effort amongst 37 partners from across Europe, including: shipyards, material developers, composite manufacturing companies, research organisations and certification bodies. The project work is carried out by this consortium in close collaboration with the E-LASS network and FIBERSHIP project. The RAMSSES project commenced in 2017 with a 4-year duration and a total project budget of 13.5 million Euro. Further information can be found at: https://www.ramsses-project.eu/.

The RAMSSES project features the development of 13 commercial case studies related to various ship designs and can be categorised into three groups: composite structures, components and equipment, and steel and repair. Composite structure case studies include internal walls and superstructures for cruise ships and multi-purpose vessels, modular cabins for passenger vessels, modular decks for RoRo vessels, aluminium composite panels for workboats, and a custom-built composite hull for a patrol vessel. Components and equipment case studies include additive manufacturing of propeller blades, composite rudder flap, and modular panels for less critical internal structures using composite and bio composite materials. Steel and repair case studies include high tensile steel decks, welding procedures for high tensile steel structural details, and patch repair procedures for steel and composite ship structures (RAMSSES, 2017).

As outlined in Chapter 1, one of the key limitations for composites in commercial ship structures are the requirements for fire safety. All case studies with RAMSSES featuring primary and/or internal composite structures must address this challenge. SOLAS regulations have only recently been amended to allow the use of polymer-based composite materials for critical ship structures due to fire safety concerns: polymer-based composite materials are combustible and produce harmful toxic fumes. The amendment states that the designer/manufacturer must prove, for any structure featuring polymer-based composites, an equivalent level of safety compared to conventional steel structures. This is done via risk-based analysis and is both costly and time consuming, requiring material and structural testing. The RAMSSES project aims to create a "fast-track" process to certification by undertaking this costly and time-consuming process for all relevant case studies.

The composite hull manufacturing case study featured in this thesis is conducted as part of the custom-built composite hull case study within the RAMSSES project. The complete work package concerns the fast track to approval of a 75m composite patrol vessel; including development of a novel resin system, product and manufacturing process design and physical testing of materials and structures. This work is conducted as a joint effort by DAMEN Shipyards, Infracore Company, Airborne UK, Bureau Veritas, Evonik and TNO. Structural design of all ship elements, including the hull shell, is conducted by DAMEN. The approval will be realised through the production and structural testing of a full-scale demonstrator section, which is an accurate representation of the hull height (6m) and thickness of all structural elements but is much shorter in length than the full 75m hull. Figure 15 outlines the demonstrator section that shall be produced.

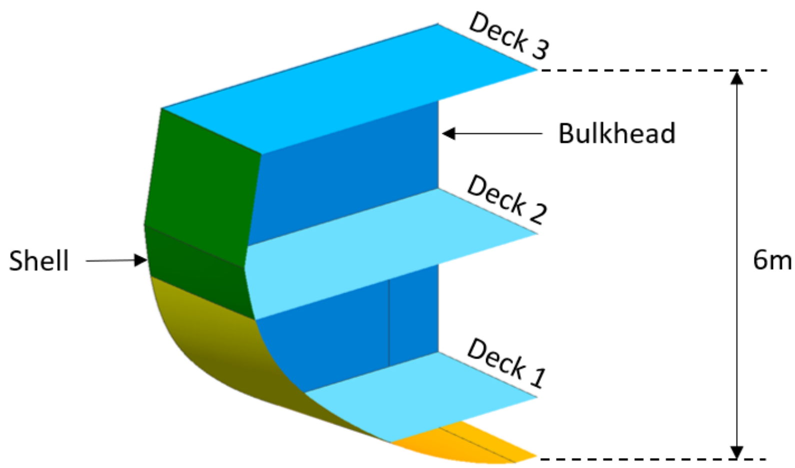


Figure 15: Hull shell demonstrator section (credit: DAMEN Shipyards)

The work conducted by the author at Airborne UK focuses solely on the hull shell, transforming DAMEN's structural design into a manufacturable product. The work conducted by the author at Airborne UK covers:

- Design of a suitable manufacturing process for a fully composite hull shell
- Design modifications to the hull shell to improve manufacturability
- The manufacture of a full-scale demonstrator section of the hull and additional test pieces
- Development of a manufacturing process concept for a 75m hull shell, including an investigation into automated manufacturing solutions.

In addition to the responsibilities of directing and conducting the technical work listed above, the author of this thesis also acted as the key representative for Airborne UK within the RAMSSES project, being responsible for project management and administrative tasks, project planning, communication with other consortium members, and the creation and submission of project deliverables on behalf of Airborne UK. The bulk of this work was conducted within an 18-month period.

Due to the limited project timeframe, and the fact that the author was predominantly responsible for all aspects of the work, this manufacturing study will focus on the rapid development of a manufacturing process in an industry setting. It is hoped that the work presented in the following chapters will enable the marine composites industry to implement a rapid process development approach that will reduce project development cost and duration by combining experimental studies with expert knowledge, enabling engineers to gain an understanding of the process using only a limited number of experimental trials.

3.2.1 Composite Hull Shell Initial Specification

Prior to the selection and refinement of a suitable manufacturing process, it is important first to consider the specific structural and quality requirements that must be met. The following requirements were determined jointly amongst the RAMSSES project consortium. It is important to note that this is a research (and thus learning) exercise to understand what is possible in an industrial environment. The suitability of these requirements shall be evaluated after the demonstrator manufacture and are used throughout this work to guide the development of a suitable process and quantitatively assess the solutions presented. The initial project specification is presented below, from which quantitative requirements are extracted from this list and used as project requirements to guide process development. Some of these requirements are further developed within this chapter. A final list of quantitative requirements is presented in the conclusion of this chapter.

- **Structural geometry:** DAMEN Shipyards provided the desired hull geometry and demonstrator tool surface (further details available in Section 3.8), as determined via the initial structural sizing calculations conducted by DAMEN. The hull shell is to be manufactured as a single, continuous structure, with a smooth outer surface finish mirroring the steel tool surface provided by DAMEN. To accommodate suitable bond thicknesses between decks, bulkheads, and shell during the hull assembly, it was jointly decided that bonding surfaces should not vary by more than +/-5mm relative to the structural design schematic. This tolerance was applied to the inner and outer surfaces of the hull shell demonstrator to act as a requirement, and thus a way to quantify the geometric accuracy.
- **Materials:** Glass fibre and toughened vinyl ester resin (developed by Evonik, RAMSSES project partner). No structural foam core material is prescribed, and the choice lies with the author (although the foam properties must be compatible with the structural design provided by DAMEN).
- **Laminate construction:** Ply construction and thickness/weight to be determined as a joint decision between structural designers (DAMEN) and manufacturer (Author on behalf of Airborne UK). Continuous fibres are required in 4 directions within hull shell structure. Laminate stacking sequence to be determined via initial structural calculations by DAMEN, and later refined if necessary (by author) to accommodate manufacturing procedures. Continuous fibres are required across the circumference of the hull (i.e., up the height of the demonstrator).
- **Fibre weight fraction:** 65% - 72% fibre weight fraction for structural laminates.
- **Structural weight:** No specific structural weight target was given for the hull shell demonstrator section. Specific targets for structural weight have been incorporated into the structural design of the entire vessel and are therefore beyond the scope of this hull shell manufacturing study. Weight is assumed to be acceptable if the material, laminate and geometric requirements are met.
- **Cost:** No specific cost goal is set for the hull shell production. The purpose of this research is to determine the technical feasibility of the manufacturing process. Further refinements to cost and commercial applicability will come after this study.
- **Manufacturing process duration:** No specific goal was set; however, an estimated process duration is presented in Section 3.5 based upon industry experience and the selected manufacturing process. This will be presented as a process requirement at the end of this chapter.
- **Manufacturing process robustness:** The manufacturing process will be conducted in a factory/shipyard where environmental conditions such as ambient temperature, relative humidity and level of air contamination are not tightly controlled. The manufacturing process (especially

the infusion stage) must therefore allow for typical variations in ambient environmental conditions within the following ranges: 15°C to 35°C, 30% (at 35°C) to 85% Relative humidity. The scale of the manufacturing challenge, combined with the use of manual labour techniques, means that the manufacturing process must be insensitive to realistic manual manufacturing tolerances. These tolerances are explored in further detail in Section 3.8. A robust manufacturing process is therefore defined as a process that can produce a part that meets the requirements of this specification whilst tolerating variations in ambient conditions and manual production techniques. These variations shall be identified throughout this chapter.

- **Allowable defects:** The following allowable laminate defect criteria was determined during joint discussions between DAMEN and Airborne UK, based on prior experience with manufacturing marine composite structures. These acceptance levels were determined prior to the manufacturing study and are reviewed for their suitability/relevance upon inspection of the demonstrator in Chapter 5. The acceptance criteria are based upon the defined defects and levels of acceptance as detailed in ASTM D 2563 (ASTM, 1998). Defects are detected via visual inspection after product manufacture. Acceptance is defined by either a maximum allowable dimension or "none", which equates to no such defect visible within the part. The frequency of allowable defects is defined in ASTM D 2563 as:

  - Acceptance level 1: None.
  - Acceptance level 2: No more than 1 defect within 10 inches. No defect areas within 2 inches of each other.
  - Acceptance level 3: No more than 2 defects within 5 inches. No defect areas within 1 inch of each other.

  The defect acceptance criteria are presented in Table 2. These are all used to assess the structural quality of the final demonstrator.

  An acceptable tolerance for fibre/ply alignment was not included within the defect acceptance criteria. This is discussed further in Section 3.8, during which a proposition is presented to measure and control this variable based upon realistic manufacturing tolerances.

Table 2: Composite Hull Shell Laminate Defect Acceptance Criteria (ASTM, 1998)

Defect	Level of acceptance	Definition of acceptance level
Chip	3	Small piece broken off an edge or surface. **Max. dimension: 6.5mm.**
Crack	1	Separation of the laminate, visible on opposite surfaces, extending through the laminate. **None.**
Crack, surface	3	Crack on laminate surface only. **Max length: 6.5mm.**
Crazing	2	Fire cracks at or under laminate surface. **Max. dimension: 13mm.**
Delamination, edge	3	Separation of material layers at edge of laminate. **Max. dimension: 6.5mm.**
Delamination, internal	1	Separation of material layers within laminate. **None.**
Dry-spot	2	Area where reinforcement has not been wetted with resin. **Max. diameter: 9.5mm.**
Foreign inclusion (metallic)	1	Metallic particles within laminate that are foreign to its composition. **None.**
Foreign inclusion (non metallic)	3	Non-metallic particles within laminate that are foreign to its composition. **Max. dimension: 1.5mm.**
Fracture	1	Rupture of laminate surface without complete penetration. **None.**
Air bubble (void)	3	Air entrapment within laminate. **Max. diameter: 3mm.**
Blister	1	Rounded elevation on laminate surface. **None.**
Burned	1	Discoloration, distortion or destruction of laminate surface due to thermal degradation. **None.**
Pimple	3	Small, sharp, conical elevation on surface of laminate. **Max. diameter: 3mm.**
Pit (pinhole)	3	Small crater in laminate surface. **Max. diameter: 0.8mm, depth <20% laminate thickness.**
Porosity (pinhole)	3	Presence of numerous visible pits. **Max. 50 per unit area for acceptance level 3.**
Pre-gel	3	Unintentional additional layer of cured resin over laminate. **Max. dimension: 13mm, height within surface tolerance.**
Resin-pocket	3	Accumulation of excess resin in a localised area. **Max. diameter: 6.5mm.**
Resin-rich edge	3	Insufficient reinforcement at edge of laminate. **Max: 0.8mm from edge.**
Shrink-mark	3	Depression on surface of laminate. **Max. diameter: 14mm, depth <25% laminate thickness.**
Wrinkles	3	Waviness in reinforcement material within laminate. **Max. dimension: 25mm, depth >15% laminate thickness.**

3.3 Research Methodology

Development of a suitable manufacturing process for the RAMSSES hull shell, and the subsequent production of the full-scale demonstrator is a complex research challenge. Furthermore, strict timeframe and budget limitations meant that some technical decisions had to be made at an accelerated pace, which in some cases led to the need to develop and implement technical solutions within as little as 5 days. This resulted in a need for a rapid manufacturing process development approach.

The first stage of this approach is to identify the most suitable manufacturing process and the key manufacturing challenges that will form the focus of this study. An Input-Output (IPO) model is then used to link the project requirements to the selected manufacturing process and define the key inputs and outputs of the manufacturing process development procedure. IPO models are commonly used in software engineering to map the architecture of a process or system (Goel, 2010). An IPO approach was selected for this rapid process development activity to identify and collate the known and unknown inputs and outputs between the structural designers and the manufacturer (the author) within this collaborative project. Some inputs are derived from the project requirements, whilst others must be defined by the author. The latter are used to generate a list of research questions that must be answered throughout this manufacturing study in order to define the remaining inputs and conduct the required development steps. Process outputs are used to evaluate the success of the proposed solutions. This approach helps to focus the development work on the key research challenges whilst ensuring the project requirements are met. The IPO model is presented in Section 3.6.

The research questions are answered individually throughout this thesis following a “Plan, Do, Check, Act” approach (which was stated in Section 1.5.2 as being the fundamental methodology for conducting the research presented in this thesis). Figure 16 outlines the procedure used by the author to address the manufacturing challenges based upon the Plan, Do, Check, Act approach. This procedure is based upon the need for the rapid and cost-effective acquisition of accurate and representative quantifiable data to support decision making during the rapid development of novel, large-scale composites manufacturing processes. Two methods are presented for acquiring this data: knowledge capture from experts, and experiment/simulation. The first two steps of this flow chart are conducted when generating the IPO model.

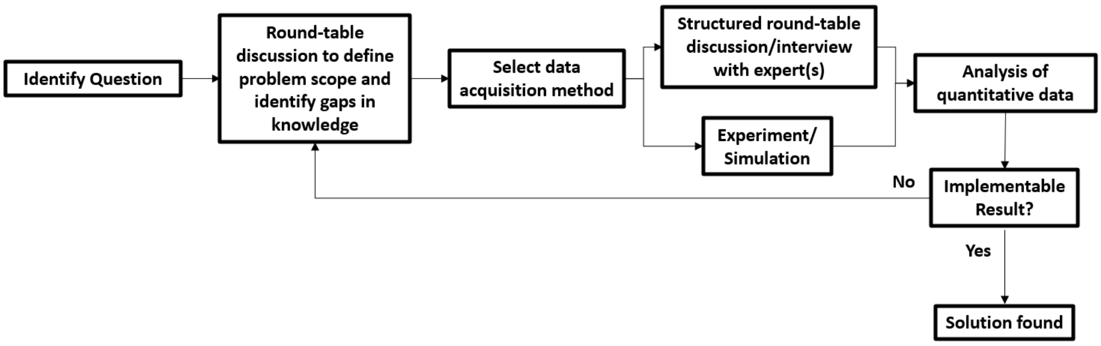


Figure 16: Plan, Do, Check, Act methodology applied by the author to solve key research challenges encountered during the rapid development of a large-scale composites manufacturing process

Representative physical experiments and simulations are useful tools that can be used to gain a detailed understanding of a specific manufacturing process. However, in some cases an experimental or simulation approach may not be cost effective due to the vast number of potential options that must be considered. The experimental/simulation approach is therefore supplemented by the collection and analysis of marine industry based tacit skills and knowledge bases, enabling accelerated decision making based upon prior experience whilst limiting the cost of detailed analytical studies where appropriate. This knowledge was gathered during structured round-table discussions with industry experts both internal and external to Airborne UK. The author contributed to these discussions and compiled this information into evaluation matrices to enable a quantitative evaluation and comparison of numerous solutions against a set of predefined evaluation criteria (see Table 3 for an example). Each option was given a numerical score corresponding to each evaluation criteria. The specific details of each evaluation (i.e., the options and evaluation criteria that were considered and their corresponding scores) were determined during the structured discussions. The evaluation criteria were assigned weighting scores to determine their relative importance. A colour coded scoring system (green = 3, yellow = 2, orange = 1, red = 0) is used to score each option against the evaluation criteria, with the latter being assigned weighting scores from 1 to 3. Higher scores indicate better solutions and greater importance. This simplistic scoring system was selected to best support the need for quick, qualitative assessments in an industrial setting and avoid unnecessary levels of complexity. The totals of the weighted scores are calculated for each option and used to make quantitative comparisons for each research question. These scores indicate the most suitable option(s) and are incorporated into a final discussion to justify the selection made by the author. Due to the qualitative nature of these assessments, these scores are not treated as definitive results, but rather as a useful indication of which options are most suitable and which options can be dismissed. In some cases, it may be appropriate to combine two or more options to create hybrid solutions based upon the results of the evaluation.

This methodology was used throughout this thesis to aid complex decision making. The collection and analysis of marine industry-based knowledge is primarily used in this chapter to support top-level decisions such as the selection of a manufacturing process and constituent materials, whilst the experimental approach is widely used in Chapter 4 to support detailed refinements to the manufacturing process.

Three research questions are defined to guide the selection of a suitable manufacturing process and identification of key manufacturing challenges. An IPO model is then applied to the selected manufacturing process to identify further research questions that will guide the rapid process development procedure through the remained of this chapter. A list of all research questions that were asked during this process is presented at the end of this chapter in Table 23, Section 3.9.

3.4 Selection of a Suitable Manufacturing Process

There are numerous composite manufacturing processes that are currently implemented across multiple industries. Selecting the most suitable process is a critical first step, as this will influence the cost and duration of the process, and the quality/properties of the part. This decision will create a starting point upon which further modifications and refinements to the process can be made later in this work. The Plan, Do, Check, Act methodology outlined in Section 3.3 was used to determine most suitable manufacturing process.

> **Question:** What is the most suitable composite manufacturing process for a 75m long hull shell?
>
> **Data acquisition method:** Structured round-table discussion with experts and review of relevant literature (Potter, K., 2014).

Only the most compatible manufacturing procedures for the 75m hull shell were considered (selected based upon expert opinion). The following evaluation criteria were identified as being the most important factors to consider when selecting a composites manufacturing process for the given case study based upon the initial project requirements and discussions with experts.

- **Cost:** The process must allow for affordable production of the hull shell. As this is a large marine structure (with large design safety factors), reducing costs is essential for producing a structure that is commercially viable and competitive with existing steel structures.
- **Size:** The hull shell is 75m long, 6m high and up to 275mm in sectional thickness. Handling and laying up large plies by hand on large, near-vertical tool surfaces is difficult, costly and poses unacceptable risk to the workforce. Customised tools will therefore need to be developed to

accommodate the size of the structure and overcome tool access limitations. The selected manufacturing process must be compatible with such solutions and scalable to the size of the structure. Due to the challenges relating to the size of the structure, inherent simplicity in the manufacturing process is preferred to limit development time and cost. Furthermore, current market trends indicate a global interest and slow adoption of composite materials into even larger ship structures. Therefore, the manufacturing process developed in this thesis should be scalable and applicable to even larger structures.

- **Geometry:** The hull shell is predominantly a single-curvature structure across most of its 75m length, with the exception of localised complex double curvature regions at the bow and stern. The current design iteration requires that the hull shell be manufactured as a single, continuous part. Due to the curvature of the hull shell, parts of the structure must be manufactured (near) vertically, presenting unique manufacturing challenges relating to the deposition and consolidation of composite materials on the tool.
- **Production rate:** It is proposed that initial production rates are low, with only a single hull being manufactured at a time. A single set of tooling is therefore sufficient during the first years of production.
- **Structural quality:** The hull shell is a critical structural member of the ship assembly, and therefore must be constructed to a high quality, as detailed in the structural requirements of Section 3.2.1.
- **Compatibility with shipyard:** Shipyards are typically built to manufacture large steel structures. It is assumed that the shipyard employees will need to be trained to successfully execute the selected manufacturing process. Process simplicity is therefore preferred such that implementation in a shipyard is possible with minimum disruption to other standard manufacturing/repair techniques and facility layout. The process must also be robust and able to cope with typical variations in the shipyard environment that are defined in Section 3.2.1. These variations will have a significant impact on the infusion process. Furthermore, air quality is uncontrolled, meaning air contaminants, windy conditions and sea spray are all possible. A clean room environment should be avoided if possible due to high costs associated with such a large, environmentally controlled facility. The manufacturing process therefore needs to be robust and able to accommodate variations in ambient environment. In this way, the manufacturing process will be more compatible with current shipyard practices, and therefore result in lower costs associated with switching to composite structures.

Table 3 evaluates the four most suitable manufacturing processes against the above criteria. The total scores indicate that hand lamination and resin infusion are the two most suitable manufacturing process. This result is further supported by the fact that similar large composite structures such as yachts and wind turbine blades are currently manufactured using hand lamination and infusion techniques. Based on this analysis, it is possible to dismiss RTM and prepreg processes due to their lower overall scores. The greatest limitations of these two options appear to be cost and size, resulting in relatively ineffective commercial solutions compared to hand lamination and infusion.

Table 3: Selection of suitable manufacturing process for composite hull shell.

Criteria *(Weighting)*	**Hand lamination**	**Vacuum bag resin infusion**	**Resin Transfer Moulding**	**Prepreg layup**
Cost *(2)*	Low process complexity with minimal equipment and infrastructure required. Material costs low.	Similar costs as for hand lamination, but with additional infusion consumables and equipment.	High setup costs due to complex male and female tooling required. Low material and operational costs.	High material costs. Oven heating required, further raising costs of infrastructure
Size *(3)*	Process can be scaled up easily due to limited dependency on supporting infrastructure and equipment.	Process can be scaled up easily due to limited dependency on supporting infrastructure and equipment, assuming room temperature curing resin is used.	Rigid male and female tooling not practical at this scale.	Autoclave is not practical at this scale. Some limited heating + vacuum bag compaction would be possible.
Geometry *(2)*	Geometry limitations are defined only by tooling and material selection. Dry reinforcement is generally easier to drape to complex geometries.	Geometry limitations are defined only by tooling and material selection. Dry reinforcement is generally easier to drape to complex geometries.	Geometry limitations are defined only by tooling and material selection. Dry reinforcement is generally easier to drape to complex geometries.	Geometry limitations are defined only by tooling and material selection. Prepreg is generally harder to drape to complex geometries.
Production rate *(1)*	Simple process with few steps meaning production rate is faster than alternatives.	Similar to hand lamination, however additional bagging and infusion steps will increase process duration.	Second rigid tool surface significantly speeds up process by eliminating lengthy bagging process.	Similar to the infusion process in terms of process duration. Layup, bagging and cure are similar for both.
Structural quality *(3)*	Manufacturing process is not sealed from ambient environment, so the risk of contaminants and defects is high. Resulting fibre volume fraction is low.	Process is sealed from ambient environment, so risk of contaminants is low. Vacuum bag will likely not form a robust seal at this scale, meaning air leaks are possible.	Second rigid tool surface is more robust than vacuum bagging. Low risk of defects/leaks.	Sealed process combined with prepreg materials will lead to good fibre volume ratios and reduced risk of defects. Less susceptible to leaks compared with infusion process.
Compatibility with shipyard environment *(1)*	Simple process with limited dependency on expensive equipment. Some personnel training required. Process is not sealed, so more susceptible to contamination and potential for greater exposure of harsh chemicals to workforce.	Personnel training required for layup, bagging and infusion. Dependency on specialised equipment. Sealed process, less risk of contamination and chemical exposure to workforce.	Personnel training required for layup, bagging and infusion. Dependency on specialised equipment. Sealed process, less risk of contamination and chemical exposure to workforce.	Simpler process than infusion/RTM with less personnel training required. Slight dependency on specialised equipment. Low risk of chemical exposure to workforce.
Total Score	29	29	27	26

Resin infusion was selected as the most suitable process due to the predicted greater structural quality achievable compared to hand lamination (which was given the highest criteria weighting (3) together with the size of structure). Based on the discussions with experts, it is thought that meeting the acceptance criteria outlined in Section 3.2.1 would be far more difficult using hand lamination in a relatively uncontrolled shipyard environment. Resin infusion offers greater levels of process control and reduced risk of defects at the expense of higher process cost and complexity. Ultimately, this appears to be an acceptable compromise. Therefore, the remainder of this thesis will focus on refining the product design and infusion process for this specific case study. A one-shot infusion process has been selected to consolidate the manufacturing process into as few discrete stages as possible. Assemblies of thin panels and stringers will be replaced with thick sandwich and monolithic regions, to create a single, continuous structure that fully exploits the potential advantages that resin infusion offers. More information on the design can be found in Section 3.8.

3.5 Identification of Key Manufacturing Challenges

The first stage of developing a manufacturing process is to define the required process stages. This helps to identify the key challenges unique to this type of application, allowing further research and development to be focused on areas of greatest importance. In this section a broad outline of the infusion process is presented.

Question: What are the key stages of a resin infusion process for a 75m long hull shell?

Data acquisition method: Structured round-table discussion with experts.

Figure 17 shows a simplified manufacturing process flow chart for the hull shell production, as determined by structured round-table discussion with experts.

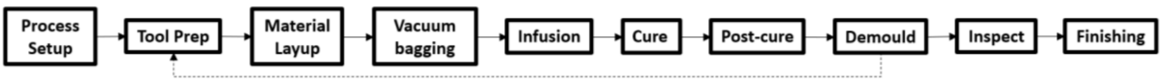


Figure 17: Vacuum bag resin infusion process outline

This process outline can then be used to identify what additional development is required at each process stage to apply this manufacturing process to the selected case study. Identifying the key areas of development helps to further focus the research activity and enable a rapid, cost-effective process development cycle.

Question: Which stages of the resin infusion process require the most development?

Data acquisition method: Structured round-table discussion with experts.

Table 4 provides brief descriptions of each process step and identifies the difficulties applying these to the specified case study. This information was acquired using the methodology presented in Section 3.3. Each process stage is given a capability score, which was determined via round-table discussion with experts and uses the same scoring system as detailed in Section 3.3. The steps identified with the lowest capability score (1) will form a key part of the research conducted in this project.

Table 4: Description and relative capability levels of all manufacturing process steps for the selected case study. Estimated duration provided for each process step for the demonstrator production.

Process Step	Description	Duration (Demonstrator)	Capability Score
Process Setup	The tooling and supporting infrastructure must be constructed. A single female tool is proposed to create a hull shell structure that is correctly oriented for bulkhead/deck assembly and has a high-quality outer surface.	60 days	**3.** Tooling and infrastructure setup procedures can be scaled up without difficulty.
Tool Preparation	The tool must be cleaned of contaminants and release agent applied prior to production. The release agent facilitates demoulding of the cured part.	1 day	**2.** Tool surface access is a key concern.
Material Layup	Dry reinforcement and structural core are laid onto the tool surface to create the dry preform. The majority of the preform is sandwich construction, with two outer laminate skins and a central foam core. Laminates are laid up as continuous plies along the circumference of the hull shell to maximise structural efficiency.	10 days	**1.** Tool surface access and layup of materials on vertical surfaces are key issues.
Vacuum Bagging	A vacuum bag is applied over the preform to create a sealed cavity against the tool surface.	2 days	**1.** Achieving a robust vacuum bag seal at this scale is challenging.
Infusion	Resin is drawn through the dry preform via vacuum suction. At the end of the infusion process the preform is full wet-out with resin.	1 day	**1.** Process is complex and sensitive to many external factors.
Cure	Resin is left to cure at toom temperature.	1 day	**3.** No special considerations required.
Post-cure	Local heating is applied to the cured part to enhance structural properties of the resin.	2 days	**3.** Existing heating solutions can be applied.
Demould	The cured part is removed from the tool. The tool can now be prepared for production of the next hull shell.	1 day	**3.** Demoulding at this scale can risk personnel safety and part quality.
Inspection	The part is manually inspected for general quality. Any repair procedures are identified at this stage.	1 day	**2.** Accessing all areas of the part is the main challenge.
Finishing	Rough edges of the part are polished and bonding areas are suitably prepared for assembly. Any repair procedures are conducted at this stage.	2 days	**2.** Accessing all areas of the part is the main challenge.

Estimates for the duration of each process step of the demonstrator production were also made based upon expert opinion, prior experience, initial predictions for man-hours, and the total project budget. These estimates are used as an initial goal for the demonstrator production later in this thesis and will also be used throughout Chapter 4 to guide the infusion process development. 1 day is equal to 8 workhours, and 4 people (including the author) are predicted to be available to work on the demonstrator manufacture. Table 4 presents the estimated total process duration from tool preparation to finishing (excluding non-repeatable tool setup) as being 21 days, equating to 672 man-hours. This value is used as a goal for the demonstrator manufacturing procedure presented in Chapter 5 and is added to the process requirements at the end of this chapter.

The estimation for infusion process duration is of particular importance as is provides a useful guide for the infusion process development in Chapter 4. This estimate is based upon the desire to complete the infusion within a single work-shift. Unlike other process steps in the demonstrator procedure, the infusion process cannot be easily paused once it has commenced. The process must be monitored by trained professionals due to the complexities and risk associated with the infusion, meaning overnight shifts may be required if the process exceeds the duration of a single working day. This is undesirable and may lead to additional process costs and complexities. The infusion process should therefore take no longer than 8 hours to complete. This is applied as a separate process requirement to guide the infusion process development.

The information presented in Table 4 indicates that material layup, vacuum bagging and infusion are the three most critical stages of the manufacturing process that require significant levels of further development. Vacuum assisted resin infusion is a potentially complex procedure, primarily due to the large number of parameters that can affect the cost and duration of the process and the quality of the part. The unique challenges of this case study further exacerbate the effects of parameter variations and can result in a highly complex and sensitive process if not suitably addressed. The following high-risk layup, bagging, and infusion challenges have been identified for this case study, which will be the focus of the manufacturing study:

- **Scale, Geometry, and Accessibility:** The scale of the infusion process is one of the key novelties of this work. Production of the demonstrator will require approximately 1 tonne of resin to be infused during a single procedure. Small variations in process parameters may compound and significantly affect the infusion process. The scale and geometry of the part reduces accessibility to the tool surface, increasing the complexity of the manual layup and bagging procedures, and thus the risk of defects forming within the laminates. The use of one-time consumable products such as resin feed tubes, tacky tape and vacuum bags further increases the risk of process failure at this scale. The vacuum infusion process requires a perfectly sealed vacuum cavity to maximise product quality. The consumable products must be assembled by hand and are therefore prone to human error, leading to small leaks which can allow air into the preform. Air leaks create voidage within the cured laminate which can have a detrimental effect on the structural properties. The scale of the part increases the likelihood of leaks, as more seals/connections must be made.
- **Vertical infusion:** A major challenge of this work is to successfully infuse resin up to 6m in height within a reasonable time frame (~8-hour typical working shift). Vacuum assisted resin infusion utilises vacuum bags on one surface of the part, which are flexible membranes that form around the preform geometry with the aid of vacuum compaction. When conducted vertically, additional gravity effects may cause the resin to collect at the bottom of the part, causing the vacuum bag to expand and distort. This can result in large resin rich areas at the bottom of the part and dry regions at the top. In extreme cases, large resin pockets could form under the vacuum bag, creating geometric deformities. Additional novelties of this part such as the 6m maximum height, 275mm maximum thickness and variety of structural features add further complexity to this work.

- **Variable shipyard environment:** The infusion process must be applicable to a standard shipyard environment. These environments are not tightly controlled which will lead to further variations in process parameters. The proposed manufacturing process should therefore be robust and able to facilitate variations in ambient temperature and relative humidity.

The following workplan is presented to address these key issues. Figure 18 outlines the main areas of research that will be conducted within the remainder of this thesis.

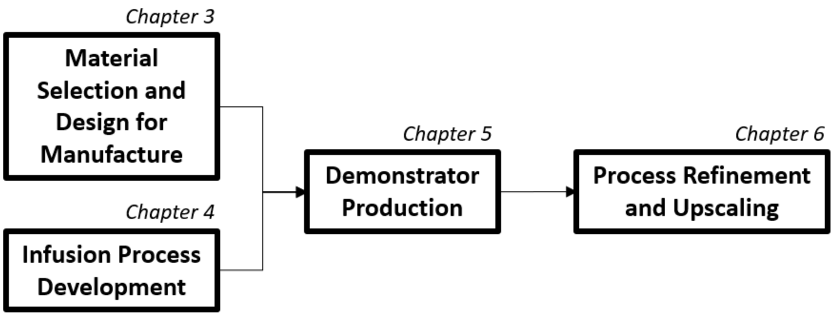


Figure 18: Outline of work required to develop a suitable manufacturing process

- **Material Selection and Design for Manufacture:** The remainder of this chapter will focus on material selection and modifications to the hull shell's baseline design to improve manufacturability. This includes refinement of local structural details and development of a ply book.
- **Infusion Process Development:** Chapter 4 presents the research undertaken to develop a suitable infusion strategy. This work will address the challenges related to vertical infusion, scale, geometry, and accessibility.
- **Demonstrator Production:** A record of the demonstrator production is presented in chapter 5. This work includes the development of the overall manufacturing process (excluding infusion) that is outlined in Figure 17. Challenges related to variable shipyard environment, scale, geometry, and accessibility are addressed in this work. The previously developed infusion process is applied here.
- **Process Refinement and Upscaling:** The final chapter in this thesis features a further iteration of the manufacturing concept for the scaled up 75m hull shell. This work builds on the suggested improvements outlined in chapter 5, exploring the suitability of automated manufacturing techniques to further improve process repeatability, accuracy, and process control, whilst reducing production duration and costs. The key findings of this work are also used to generate a manufacturing concept for a composite tidal turbine blade.

3.6 IPO Model

The Input-Output (IPO) Model introduced in Section 3.3 is applied to the selected manufacturing process to identify key inputs and outputs for this rapid development procedure. Figure 19 shows the major steps in the infusion process development and the input and output links between them. Each step in the development process represents a major decision or concept generation following the Plan, Do, Check, Act approach (Decision matrices, knowledge capture and/or experiments, see Figure 16). Fixed inputs are those which have been extracted from the project requirements in Section 3.2.1. Variable inputs are those which must be defined by the author to facilitate the process development steps. Intermediate outputs are defined as variables, data, or concepts that are generated as a result of the decisions made within development steps and used as inputs for subsequent development steps. Final outputs represent the results generated through application of the developed manufacturing procedure which are evaluated against the project requirements. The remainder of this chapter will focus on the development steps related to material selection and structural design. Infusion strategy development is detailed in Chapter 4, whilst an account of the demonstrator manufacture (including preform layup, vacuum bagging, infusion, and part inspection) is provided in Chapter 5.

The first step in the rapid process development activity is to define the variable inputs. Research questions are generated based upon these variable inputs and are presented throughout this chapter and listed in Table 23 in Section 3.9. Decisions are made using evaluation matrices, with the intermediate outputs being used as evaluation criteria where appropriate. Research questions were also generated from the intermediate outputs that were considered critical for this case study, such as resin gel time, resin/fibre compatibility, and laminate bulk factor. The author conducted experiments to quantitatively evaluate these variables where possible.

3.7 Material Selection and Qualification

Selection of suitable constituent materials is a critical step towards developing a successful manufacturing process that is robust and able to tolerate the variable manufacturing environment. It is also important to understand how these materials behave when handled and processed. This section details the process used to rapidly select suitable materials that are yet undefined for the hull shell case study. The methodology outlined in Section 3.3 was used to support material selection decisions. It is important to note that these decisions had to be made at an accelerated pace. This section also includes further analysis and refinement (if necessary) of the materials that have already been defined in the initial specification (Section 3.2.1). This section primarily focuses on the manufacturing aspects that influence material selection.

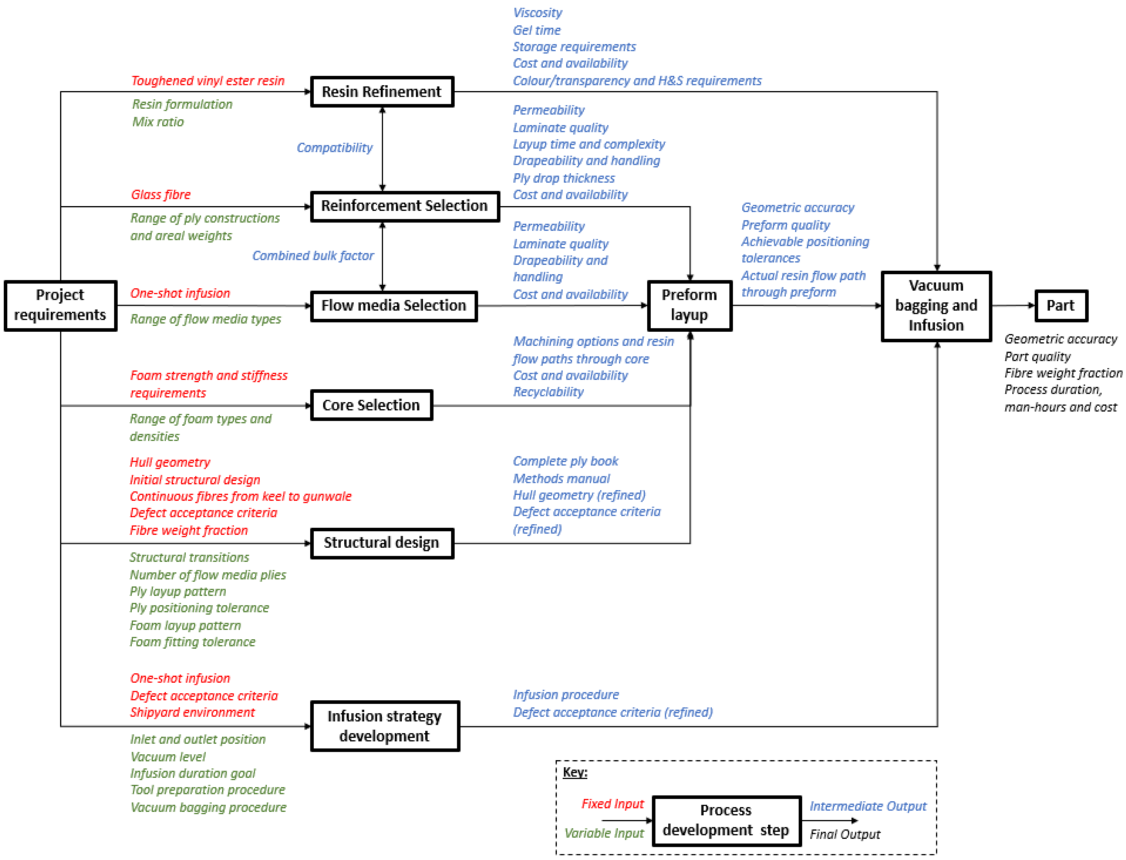


Figure 19: IPO Model for rapid development of hull shell manufacturing process

3.7.1 Reinforcement

It is estimated that approximately 2 tonnes of glass reinforcement are required to produce the hull shell demonstrator, leading to high material costs and lengthy layup procedures. Glass fibre was selected over alternatives such as carbon, aramid, or natural fibres during development of the initial specification as it provides the best compromise between structural performance and cost for the selected case study.

3.7.1.1 Reinforcement Selection

As outlined in the initial specification (Section 3.2.1), ply construction and weight are to be determined jointly between the manufacturer (the author on behalf of Airborne UK) and the designer (DAMEN). During initial discussions with the shipyard, it was suggested that continuous fibres would be required in 4 primary directions across the hull shell surface to support the structural loads. Reinforcement selection was primarily made by the author based upon manufacturability concerns due to the novelty and technical difficulty of this manufacturing study. A rapid, cost-efficient material selection was made by only considering the most commonly available reinforcement configurations and weights that best fit the initial specification.

Question: What is the most suitable reinforcement ply construction for the case study?

Data acquisition method: Structured round-table discussion with experts and material suppliers.

The following evaluation criteria were defined:

- **Layup Time:** A relative comparison of the time taken to layup a 275mm thick laminate on the demonstrator tool. Thinner plies will result in a larger total number of plies to layup. The greater the number of plies, the longer the layup is assumed to take.
- **Drapeability:** The relative ease in which each option can conform to the single and double curvatures and geometric transitions featured in the hull shell geometry. The large curvature radii and limited double curvatures over the hull shell mean this factor is less critical. It should be noted that this is a basic comparison and does not account for local fibre orientations with regards to the geometry, layup sequence/approach, or stitching patterns. Drape simulations could be applied in future work to optimise material selection activities but is beyond the scope of this study.
- **Layup Complexity:** A relative measure of the complexity of the layup procedure for each option. Multiple ply orientations will lead to greater layup complexity.
- **Material Integrity/Handling:** A relative measure of how well each material holds together when handled in large plies (2-9m length, 1-3m wide). Materials that are more easily damaged during handling will lead to a greater level of defects within the laminate. The size and geometry of the structure means that ply damage is a much greater risk than for smaller/simpler products.
- **Ply Drop Thickness:** Thicker plies can lead to thicker transitions in laminate thickness when plies are dropped within the structure (referred to as ply drops). This is an important factor when considering geometric tolerances and requirements, however the scale of the structure compared to the ply thicknesses considered mean that this criterion is less critical than the others above.

Table 5 indicates that 1200gsm quadaxial is the most suitable material for this case study due to faster and simpler layup procedures. A 1mm thick non-crimp 1200gsm quadaxial fabric with a stacking sequence of [+45/-45/0/90] was chosen over similar products for the following reasons:

- The selected material has regular gaps between the 0° tows for improved resin flow. The improved permeability is particularly important for the infusion of the thick monolithic sections.
- This material can be supplied with adhesive backing to better support vertical ply layups.
- This material is a standard type of glass reinforcement that is more affordable and readily available compared to more bespoke products.

Table 5: Evaluation of the effect of different reinforcement configurations on the manufacturing process

Criteria	600gsm			1200gsm		
	Unidirectional	**Biaxial**	**Quadaxial**	**Unidirectional**	**Biaxial**	**Quadaxial**
Layup time *(3)*	More plies to layup.	More plies to layup.	More plies to layup.	Fewer plies to layup.	Fewer plies to layup.	Fewer plies to layup.
Drapeability *(2)*	Will conform to the single curvature of the hull shell. Will be difficult to drape around double curvatures.	Will conform to the single curvature of the hull shell and most double curvatures around bow and stern. Thinner plies will bend more easily around sharp geometric transitions.	Will conform to the single curvature of the hull shell and most double curvatures around bow and stern. Thinner plies will bend more easily around sharp geometric transitions.	Will conform to the single curvature of the hull shell. Will be difficult to drape around double curvatures.	Will conform to the single curvature of the hull shell and most double curvatures around bow and stern. Thicker plies may be more difficult to bend around sharp geometric transitions.	Will conform to the single curvature of the hull shell and most double curvatures around bow and stern. Thicker plies may be more difficult to bend around sharp geometric transitions.
Layup complexity *(3)*	Plies must be laid up at multiple different orientations on the tool.	Biaxial construction reduces the number of ply layup orientations.	All plies laid up in the same direction on the tool.	Plies must be laid up at multiple different orientations on the tool.	Biaxial construction reduces the number of ply layup orientations.	All plies laid up in the same direction on the tool.
Material integrity/ Handling *(3)*	Large plies can fall apart when handled due to light stitching in off-axis direction.	Additional fibre direction results in a more robust material.	Four fibre directions result in a significantly more robust material.	Large plies can fall apart when handled due to light stitching in off-axis direction.	Additional fibre direction results in a more robust material.	Four fibre directions result in a significantly more robust material.
Ply drop thickness *(1)*	600gsm results in shallower ply drops.	600gsm results in shallower ply drops.	600gsm results in shallower ply drops.	1200gsm results in deeper ply drops.	1200gsm results in deeper ply drops.	1200gsm results in deeper ply drops.
Total Score	**14**	**24**	**30**	**19**	**27**	**33**

3.7.1.2 Reinforcement Qualification

Having selected a suitable reinforcement material, two brief investigations were conducted to check material compatibility and quantify processing behaviour. The first investigation conducted was an infusion trial with the selected reinforcement and resin system to ensure the fibres, sizing and resin can be combined to produce a simple thin laminate that meets the requirements detailed in Section 3.2.1. As the resin system had already been defined in the initial specification, the purpose of this test was to determine whether the reinforcement was compatible with the resin, or whether modifications would be required to the fibres and/or sizing.

Question: Can the selected constituent materials be combined to form a simple laminate of adequate quality?

Data acquisition method: Experiment.

To test the material compatibility, single-ply strips (0.15x0.5m) of the quadaxial reinforcement were laid onto a pre-released aluminium tool surface. A vacuum bag was applied over the panels, with a resin inlet and vacuum outlet positioned across opposite ends of the panel. The infusion was conducted at 20°C and -0.9bar vacuum. The infused panels were left under -0.9bar vacuum for 24 hours at 20°C to cure prior to debagging and visual inspection. The experimental setup is shown in Figure 20. This investigation was expanded to also include a second type of fibre and resin system that were currently being used on another commercial project at Airborne UK. This combination of resin and fibres was known to create a laminate of good quality, and thus provided a useful reference. These materials were Prime 27 resin (extra slow hardener) and a Saertex quadaxial glass non-crimp reinforcement (different stitching and sizing to the material selected for the ship hull). These alternative materials were selected as "backup" materials in the event that there were unforeseen processing or development issues with the selected materials. Therefore, the compatibility of these alternative materials with the selected materials was also tested in this study. Four simultaneous panel infusions were conducted with the following resin/fibre combinations (Table 6).

Table 6: Fibre and resin combinations tested during initial compatibility study

Panel	Reinforcement	Resin	Cured panel fibre weight fraction (%)
1	Saertex Glass non-crimp 1200gsm Quadaxial (RAMSSES)	Prime 27 / extra slow hardener	66.53
2	Saertex Glass non-crimp 1200gsm Quadaxial (RAMSSES)	Albidur 3.2 VE Hull (Mix 4, see Table 10)	65.31
3	Saertex Glass non-crimp 1200gsm Quadaxial (other)	Prime 27 / extra slow hardener	69.11
4	Saertex Glass non-crimp 1200gsm Quadaxial (other)	Albidur 3.2 VE Hull (Mix 4, see Table 10)	67.80

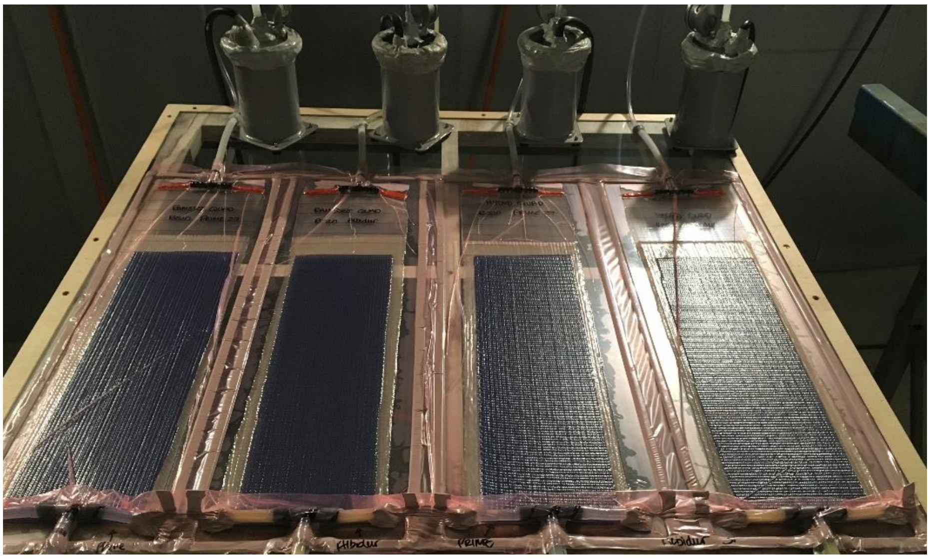


Figure 20: Initial infusion trial to check material compatibility (from left to right: Panel 1, 2, 3, 4.)

This investigation found that all four combinations of resin and fibres produced good quality laminates that met the acceptable defect criteria (Section 3.2.1). The fibre weight fractions displayed in Table 6 were calculated using measurements of cured ply thickness (see Section 4.2.1). These weight fractions all lie within the acceptable range defined in Section 3.2.1. This test concludes that all material combinations considered could theoretically be used to manufacture a large composite structure that meets the initial requirements. The alternative materials could therefore be used as a backup to reduce project risk in the event of unforeseen issues.

A second investigation was conducted to quantify the change in thickness of the dry glass reinforcement layup when under vacuum. The change in thickness must be quantified in order to create accurate preforms and avoid fibre wrinkling, bridging and other defects. These defects are most likely to form at the structural transitions between different sections of the demonstrator. Debulking is the term used to describe the process by which composite preforms are vacuum bagged periodically during the layup procedure to compact the plies.

Question: By what amount does the selected glass reinforcement material reduce in thickness due to vacuum compaction?

Data acquisition method: Experiment.

Two representative laminates were laid up on a flat aluminium tool surface and debulked to quantify the level of compaction that the selected reinforcement material experiences under vacuum. Reinforcement material was laid up by hand onto a pre-released aluminium tool surface. A vacuum bag was then applied around the preform against the tool surface. A single vacuum port was located next to the preform on the tool surface and connected to the block via a strip of flow mesh. The thickness of the preform was measured before the vacuum was applied and periodically during the compaction process. A vacuum level of -0.9 bar was used throughout this test. After 36 hours the vacuum bag was removed, and the final thickness of the laminates recorded (after no further visible change in thickness was observed). All thickness measurements were conducted by hand using a metal rule. Measurements were recorded to the nearest millimetre.

A 250x250mm test block consisting of 330 plies was tested first. The quantity of material and time required to conduct this test was substantial due to the thickness of the laminate. This thickness was required in order to be representative of the thickest regions of the hull shell case study. To save material and resources, this test was not repeated until later in the project, where the preform could be used during an infusion study. This second debulking trial was conducted on a monolithic keel preform with a stacking sequence representative of the final demonstrator.

Table 7 displays the thicknesses of the two dry glass preforms before, during and after debulking. Each thickness value is an average of four measurements taken across the preform.

Table 7: Thickness variation in dry glass preforms due to vacuum debulking.

	Section thickness (mm)	
Layup	Test block (250x250mm)	Monolithic keel layup
	300 plies + 30 saerflow	221 plies + 20 saerflow
Before debulking	380	280
Under vacuum	280	205
After vacuum removed (stable after 24 hrs)	340	250
% reduction in thickness due to debulking (before vacuum is applied to after vacuum is removed)	10.53	10.71
% reduction in thickness from before debulking to under vacuum	26.32	26.79

Figure 21: Thick monolithic laminate debulk investigation

The data indicates that there is a 26% reduction in thickness for thick laminates when exposed to vacuum compaction. However, debulking procedures are of limited benefit as the dry preform springs back to approximately 90% of the original thickness when vacuum compaction is removed. Debulking procedures can be implemented within the manufacturing process, however modifications to the product design, such as avoiding sharp geometric transitions, are required to completely avoid defective laminates. These modifications are discussed in further detail in Section 3.8.

3.7.2 Resin

Resin selection is outside the scope of this thesis, and is instead conducted by RAMSSES project partner Evonik, who have developed a novel toughened vinyl ester resin system (Albidur VE Hull 3.2) for the composite hull demonstrator. This resin contains toughening particles that enable a high degree of toughness and elongation, as indicated by the resin properties in Table 8.

Table 8: Albidur 3.2 VE Hull cured bulk resin properties (RT cure with 4 parts Peroxan BP-Powder 50 W+, 0.5 parts Pergaquick A1S) – Data supplied by Evonik

Property	Unit	Typical Values
Flexural Strength	MPa	120
Flexural Modulus	MPa	2100
Elongation	%	7.5
Toughness	J/m^2	14.5
Glass Transition Temperature	°C	98
Cured density	g/cm^3	1.123

The selection and formulation of this resin is predominantly dictated by the structural requirements of the hull, however there is scope to refine the process characteristics of the resin to improve compatibility with the manufacturing process. Refinement of the resin's chemical composition was guided by manufacturing trials that were conducted by the author. To guide these trials, it was first necessary to identify the most important resin processing characteristics for the hull shell infusion.

Question: What are the most important resin processing characteristics for the hull shell infusion?

Data acquisition method: Structured round-table discussion with experts.

Table 9 identifies the most important resin processing characteristics. Following previous sections, the characteristics are given a score from 1 (orange) to 3 (green), indicating their relative importance. The characteristics given the highest score (3) are deemed the most important and will form the basis of further materials analysis. The four most important processing parameters for the resin and selected case study were determined to be gel time, viscosity, compatibility with fibres/sizing, and compatibility with infusion equipment. Compatibility of fibres, sizing, and resin was investigated in the previous section, whilst compatibility with infusion equipment was addressed via selection of a liquid catalyst and accelerator (see Table 10). Therefore, resin gel time and viscosity are investigated further in this section.

Table 9: Identification of important resin processing characteristics for selected case study

Processing Characteristic	Description	Relative Importance for selected resin and case study.
Colour/ transparency	Transparent resins enable more effective visual inspection and identification of defects within the cured laminates. Transparency is therefore preferred.	**2.** The addition of toughening particles results in a somewhat opaque white liquid. Whilst resin transparency is preferred (because visual inspection of laminate quality is important for this case study), resin toughness was deemed more important, so this material property is not modified within this project.
Health and Safety	The resin may release styrene or other harmful chemical substances into the workshop atmosphere. High levels of these substances may be harmful to the workforce and lead to additional process complexity via extra safety procedures and PPE.	**1.** Process simplicity is preferred, however additional safety procedures (such as full-body PPE, air extraction and sealed resin containers) can be implemented without a great deal of difficulty or cost.
Gel time	This is the time the resin takes to gel after all components are mixed. The gel time should be matched closely to the infusion time so that the resin gels soon after the infusion has finished. The longer the resin remains liquid after the infusion, the greater the risk of process issues affecting the part (such as resin drainage or bag leaks).	**3.** An insufficient or excessive resin gel time will have a significant detrimental effect on the resin infusion process. Therefore, this characteristic is very important.
Viscosity	This variable determines the overall speed of infusion and fibre wet-out. A resin with an excessively high viscosity will infuse too slowly and may not be able to fully penetrate the fibre tows. Excessively low viscosities can lead to resin flows that are too fast, which may not provide the resin enough time to fully penetrate fibre tows.	**3.** Viscosity will have a significant effect on the infusion process and is therefore a very important characteristic.
Compatibility with fibres/sizing	Fibres are coated with sizings to enable good chemical bonds between the resin and fibres. All three substances must be chemically compatible to produce a good quality laminate. Incompatible materials may lead to poor fibre wet-out.	**3.** Incompatible materials may result in a laminate with a high level of defects, and thus not able to meet the initial specification. This characteristic is therefore very important.
Cost	For commercial applications, the cost of the resin and any additional catalysts/accelerators must be considered.	**2.** The relative importance of this factor depends on the specific commercial application. For this research case study, cost is important, but less so than characteristics directly related to the manufacturing process.
Availability	Commercial availability will influence the cost, delivery time, and quantity of material that can be purchased. Materials that can be purchased from a range of different suppliers are preferred.	**2.** The relative importance of this factor depends on the specific commercial application. For this research case study, availability is important, but less so than characteristics directly related to the manufacturing process.
Compatibility with infusion equipment	If an injection machine is used, it must be able to process the selected materials. The viscosity, relative mix quantities, and physical state of the resin, catalyst and accelerator must be compatible with the injection machine.	**3.** An infusion machine will be used for the demonstrator production. Therefore, the resin, catalyst and accelerator should be of liquid form with viscosities lower than 500mpas at 25°C.
Storage requirements	Resins, catalysts, and accelerators must generally be stored below certain temperatures to preserve shelf life and prevent ignition. Some chemicals may require storage in refrigerated containers.	**1.** Storage requirements must be considered, however Airborne UK has facilities in place (including flame-proof cabinets and refrigerated units) to store a range of different chemical substances, so this characteristic is of relatively low importance.

3.7.2.1 Resin Gel Time

Resin gel time can be fine-tuned by varying the composition of the resin mixture. The resin is a three-part system with an accelerator; Pergaquick A3X, and a catalyst; Weloxan BP-40-S. The ratio of these additives can be varied to modify the cure time of the resin for specific temperatures.

Initial pot tests were conducted to investigate the effect of mix ratios on resin gel time. Table 10 displays the gel time for four different mix ratios. This data was kindly supplied by Evonik in response to an initial request for a 2-hour gel time by the author. A 2-hour gel time was an initial estimation based on prior experience and is thought to be sufficient time to enable full infusion of the demonstrator, provided the infusion is split into multiple sections (this infusion approach is discussed further in the next chapter).

Table 10: Gel times for different resin mix ratios.

	Mass of additive (% of resin mass)			
	Mix 1	**Mix 2**	**Mix 3**	**Mix 4**
Pergaquick A3X	0.5	2	0.25	0.5
Weloxan BP-40-S	4	2	1	1
Gel Time at 25°C	42min	20min	4h 26min	2h 37min

The data in Table 10 will act as a "recipe list" going forward. These mix ratios shall be used in later infusion trials and process development activities.

3.7.2.2 Resin Viscosity

The viscosity of this particular resin system can be modified by varying its styrene content. This was done by Evonik based on feedback from infusion trials at Airborne UK. Evonik first supplied an initial resin iteration (Albidur 3.0) to Airborne UK for initial testing with a viscosity of 500mpas at 25°C. This resin formulation was used to infuse single-ply strips (0.15x1m) of the selected reinforcement on a pre-released aluminium surface under a vacuum bag (-0.9 bar vacuum level). Panels were infused at 12°C, 20°C and 35°C using resin mix 4 (see Table 10) and the infusion methodology shown previously in Figure 20. A second set of panels were infused simultaneously with Prime 27 resin (extra slow hardener) for reference, as Airborne UK has prior experience with this resin. These tests found that the Albidur 3.0 formulation resulted in slower infusion rates across all temperatures and relatively poor fibre wet-out at 12°C and 25°C compared to the Prime 27 resin. Figure 22 shows regions poorly wet-out fibre tows distributed throughout the panel infused at 25°C, which do not meet the acceptance criteria defined in Section 3.2.1. All Prime 27 panels that were infused met the initial specification requirements.

As a result of these findings, the author requested a modified Albidur formulation with a lower resin viscosity. Based upon prior experience with large infusions at Airborne UK, it was believed that the hull shell demonstrator infusion could be achieved with the Prime 27 resin formulation. Therefore, it was requested that the next Albidur resin formulation had a resin viscosity equal to that of prime 27 at 25°C (200mpas) (Gurit, 2020). The infusion trial was repeated with this new formulation, and the results are shown in the previous section on reinforcement qualification (Section 3.7.1).

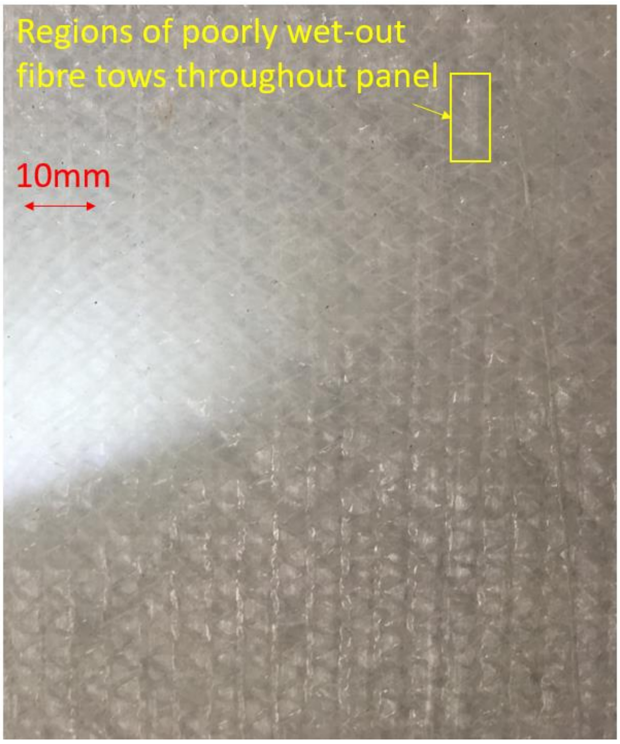


Figure 22: Poorly wet-out reinforcement within glass panel infused with Albidur 3.0 resin

Figure 23 shows the variation of resin viscosity with temperature for the final iteration of the resin system, as measured by Evonik. Unmixed resin (no accelerator or catalyst) was used for this measurement. This viscosity curve was used to estimate the viscosity of the resin at given temperatures during further infusion trials featured in this work.

Table 11: Comparison of 1m length infusions using two different resins at various temperatures

Temperature (°C)	Time to complete infusion (min)	
	Albidur 3.0 (mix 4)	Prime 27 / extra slow hardener
12	67	43
20	22	16
35	12	8

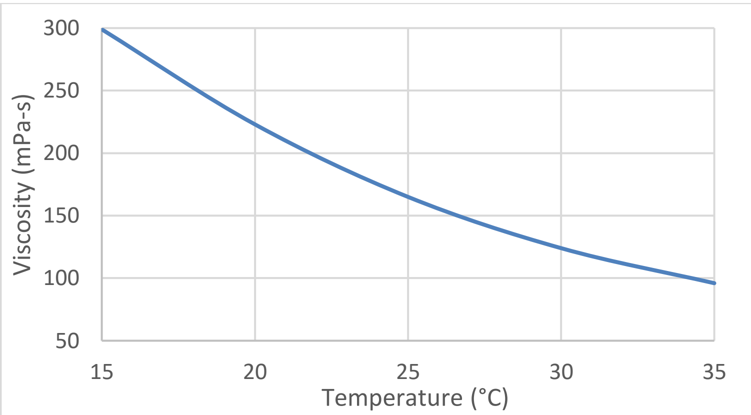


Figure 23: Resin viscosity variation with temperature

3.7.3 Core

A large majority of the hull shell is sandwich construction. The sandwich core is therefore a critical part of the structure as it greatly contributes to the overall sectional stiffness. There are many factors that influence the choice of core material, and there are many core materials available on the market.

> **Question:** What is the most suitable foam core material for the sandwich regions of the hull shell structure?
>
> **Data acquisition method:** Structured round-table discussion with experts and material suppliers.

DAMEN initially selected a range of commercially available PVC foam cores for their initial structural design, as these products provided mechanical properties that best matched their structural requirements. DAMEN utilised different densities of foam core throughout the structure to optimise structural performance (generally, increasing the densities of PVC/PET foam core leads to greater mechanical properties per unit area).

The purpose of this section is therefore to explore other commercially available foam core materials and identify the most suitable product with regards to manufacturing factors. In order to avoid costly re-design work, the foam core materials considered should match as closely as possible to the mechanical properties and densities of the foam cores selected by DAMEN.

PET and PVC foam were identified as the most suitable core materials as they are the most compatible with DAMEN's initial structural design with regards to mechanical properties and density. The following criteria were identified as being the most important for this foam core selection process. The methodology outlined in Section 3.3 was used to identify criteria, weightings, and individual scores for each option. It is important to note that specific factors influencing the structural design (such as type approval) are not included here.

- **Compatibility with initial structural design requirements:** Foam core manufacturers generally offer a range of foam cores with varying mechanical properties and densities. The specific mechanical properties and densities available varies between manufacturers. The selected material should match as close as possible to those initially selected by DAMEN.
- **Cost:** A large quantity of foam core shall be used to construct the hull shell. Therefore, the cost of the foam core will have a great influence on the overall manufacturing cost. The relative cost of each foam core option should therefore be considered.

- **Range of sheet sizes and cutting/machining options available:** Foam core is generally supplied in sheets with grooves and/or perforations to enable layup on a curved tool surface and sufficient resin flow during infusion (this is discussed in further detail in Section 3.8 and Chapter 4). The size of these sheets and the range of machining details available may vary depending on the supplier.
- **Recyclability:** Whilst the recyclability of resins and fibres falls outside the scope of this project, the existence of some commercially available recyclable foam core materials may allow for a reduced environmental impact with little-to-no compromise in other important areas such as cost and mechanical properties.

The following commercially available foam core materials were considered for this case study based upon manufacturer/distributer recommendations, prior manufacturing experience, and expert opinion. All foam core materials considered have closed cell construction to limit resin and/or water uptake.

Table 12: Comparison of different foam core materials

Criteria	PVC			PET			
	Divinycell H	**Gurit PVC**	**Airex C70**	**Divinycell PN**	**ArmaForm GR**	**Gurit G-PET**	**Airex T92**
Compatibility with structural design *(3)*	Wide range of available densities allow close match with structural design.	Limited range of products, but those offered match design.	Limited range of products that do not fully match design.	Limited range of products that do not fully match design.	Wide range of products allow close match with structural design.	The range of products offered match design.	The range of products offered match design.
Cost *(2)*	High	High	High	Low	Low	Low	Low
Range of sizes and machining options *(3)*	Standard sheet size varies depending on density. Custom machining options available.	Standard sheet size varies depending on density. Custom machining options available.	Standard sheet size varies depending on density. Sheet thickness up to 50mm. Custom machining options available.	Standard 1x2.4m sheets available for all densities of interest. Custom machining options available.	Standard 1x2.4m sheets available for all densities of interest up to 100mm thickness. Custom machining options available.	Standard 1x2.4m sheets available for all densities of interest. Custom machining options available.	Standard 1x2.4m sheets available for all densities of interest up to 100mm thickness. Custom machining options available.
Recyclability *(1)*	Not recyclable	Not recyclable	Not recyclable	Recyclable	Recyclable and made from recycled materials	Recyclable	Recyclable
Total Score	**18**	**18**	**15**	**23**	**27**	**26**	**26**

Table 12 indicates that the PET foam cores are generally more suitable for this application due to their lower cost and ability to be recycled. ArmaForm GR, Gurit G-PET, and Airex T92 are all suitable selections for this application. Only one supplier was selected to minimise costs and logistical operations. ArmaForm GR PET structural foam was ultimately selected for due to its highest score and existing relations with the local Armacell foam core distributer.

ArmaForm GR200 foam core was selected for SP1, whilst GR135 foam core was selected for SP2 and SP3. The densities of these foams are 200kg/m^3 and 135kg/m^3 respectively. This foam can be supplied with resin flow channels and perforations to aid the resin infusion process. Cuts can also be made in the foam to aid draping along curved surfaces. The foam is supplied as panels of 1000x1200x50mm in width, length, thickness respectively for the following reasons:

- The material supplier could only supply sheets of 1000x1200mm with the desired perforations and grooves (see Section 3.8 and Section 5.6.3), as the limited quantity of material required for this research project meant that it was not cost effective for the supplier to set-up a dedicated production line for this specific combination of geometry and features. The author was informed that sheets of 1.2x2.4m would be available for a full-scale 75m hull shell manufacturing process.
- After some initial trials and consultation with materials suppliers and manufacturing experts, it was concluded that thinner foam sheets will more easily drape to the curvature of the tool compared to thicker blocks. The thicker sandwich sections will therefore be constructed using 50mm foam sheets rather than 200mm thick foam pieces.
- Dividing the foam core into multiple layers allows foam panel connections to be staggered. This prevents continuous seams through the sectional thickness and produces a potentially stronger and more damage tolerant sandwich structure.

3.7.4 Flow Media

Flow media is predominantly used within the composites industry to improve resin flow during infusion processes. Flow media is a porous, low fibre volume fraction fabric formed from glass and/or synthetic polymer fibres. Layers of flow media are positioned between traditional reinforcement plies to create open channels for resin to flow. Due to its non-structural nature, the addition of flow media results in a minor knockdown in global laminate in-plane mechanical performance. Flow media is generally used in the manufacture of larger infused components such as wind turbine blades where the benefits of improved resin flow outweigh the slight reductions in mechanical performance.

Several types of flow media are available on the market. A brief material selection study was conducted to quickly identify the most suitable flow media material for this case study.

> **Question:** What is the most suitable flow media material for the production of the hull shell?
>
> **Data acquisition method:** Structured round-table discussion with experts and material suppliers, supported by experiments where required.

The following evaluation criteria were identified as being the most important factors to consider when selecting the flow media material for this case study.

- **Resin flow speed:** The primary reason for implementing flow media is to increase resin flow speed. Therefore, relative speed of infusion between different flow media options is an important factor to consider. This cannot be determined via discussion, so an infusion trial is conducted to provide a quantitative comparison. More details of this experiment are available in Appendix: A.6.
- **Drapeability:** A relative measure of how easily the flow media can be draped around single and double curvatures and steps in geometry (approx. 45° transition with 2mm radius of curvature – based upon structural transitions in initial design). A more conformable material will simplify layup procedures and reduce production costs. Drapeability around double curvatures is included in this comparison to account for the bow and stern regions within the full 75m hull shell structure. Relative comparisons were made based upon handling and draping the materials at Airborne UK.
- **Material Integrity/Handling:** A relative measure of how well each material holds together when manually handled in large plies (2-9m length, 1-3m wide). Plies will be manually handled during the demonstrator production, and materials that are more easily damaged during handling will lead to a greater level of defects within the laminate. The size and geometry of the structure means that ply damage is a much greater risk than for smaller/simpler products. The lower fibre fraction and lighter stitching of flow media compared to conventional reinforcement plies means that flow media can be more susceptible to damage during handling. Relative comparisons were made based upon handling and draping samples of the material at Airborne UK.

Three commonly available brands of flow media were considered, all 1mm ply thickness to best match the selected quadaxial reinforcement. For this comparison It was decided that all criteria would be given equal weighting.

Table 13: Flow media comparison

Criteria	Saerflow	Uniflo	G-flow
Resin flow speed (minutes to infuse 1m length, 1 ply quadaxial, 1 ply flow media)	12	16	8
Drapeability	A mesh of fibres can be draped and sheared to match most single and double curvatures featured within the hull shell geometry.	A mesh of fibres that can be draped and sheared to match most single and double curvatures featured within the hull shell geometry.	A slightly more rigid material compared to Saerflow and uniflow with a defined tows and stitching pattern. Can fit to single curvatures but more difficult to drape around sharp corners or double curvatures.
Material integrity/handling	The standard Saerflow material can distort and fall apart when handled as large plies. However, the material supplier offers a variant with additional stitching that prevents this.	The material tends to fall apart when handled as large plies.	Material is strongly held together and does not fall apart easily.
Total Score	**8**	**5**	**8**

Table 13 indicates that either Saerflow or G-flow would be best suited for this application. G-flow provides faster infusion rates, although Saerflow is easier to form around complex geometries. Ultimately, a 1mm thick Saerflow material was selected for the following reasons:

- The ability to easily form and drape the material may provide some benefits during demonstrator production, enabling an easier and faster layup process with fewer defects. This selection will also enable easier upscaling to a full hull shell that features double curvatures at the bow and stern without the need to change flow media material.
- Based upon expert opinion and previous experience with the material at Airborne UK, it was thought that the Saerflow material could provide a sufficient resin flow rate to enable the creation of a successful hull shell infusion scheme, despite providing a slower resin flow rate compared to G-flow. Whilst details of prior experience with Saerflow gained during the development and production of other commercial projects cannot be featured in this report, the reader is encouraged to refer to Chapter 4 for experimental results conducted as part of this study that justify this decision.
- Saerflow is provided by Saertex, the suppliers of the chosen glass reinforcement. Sourcing materials from a single supplier streamlines logistics.

3.8 Design Modifications to Support Manufacture

This section describes how the initial design has been modified to accommodate the selected materials and manufacturing process. DAMEN Shipyards have developed a structural design of the hull assembly as part of the RAMSSES project. The geometry of the demonstrator structural design is outlined in Figure 24 and Table 14. The demonstrator structure is uniform across the width and the circumferential length is divided into four discrete regions that increase in thickness towards the keel. Plies are laid up along the circumference of the hull shell geometry to provide continuous fibres in this direction as requested in the initial specification. The keel acts as the "spine" of the vessel and therefore experiences high levels of loading. The keel was designed as a monolithic structure to carry these loads, whilst the remainder of the structure (SP1, 2 and 3) consists of sandwich panels. Sandwich panels provide a good compromise between strength, stiffness, and weight, and are therefore used extensively to reduce the global weight of the vessel. Due to buoyancy limitations, implementation of light-weight sandwich panels is not critical at the keel, allowing for more robust monolithic structures.

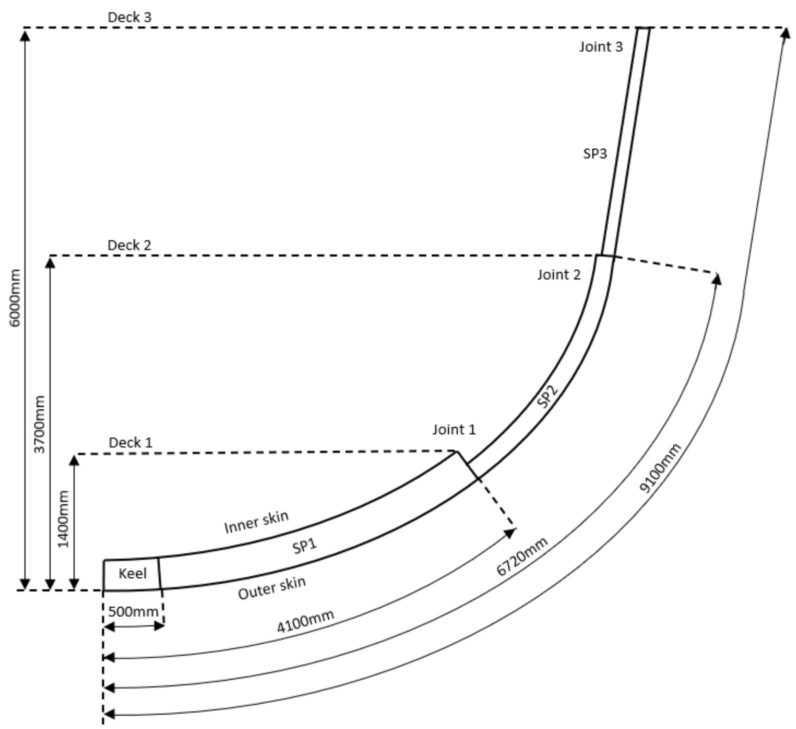


Figure 24: Initial demonstrator cross-sectional geometry

The overall size of the demonstrator is limited to the maximum tool size that can easily be transported between the UK and the Netherlands. The tool surface was limited to 2.5m wide by 9.3m circumference as this was the maximum size that could fit on a flat-bed truck (the most cost-efficient mode of transport). The demonstrator design is 2.3m wide by 9.1m circumference, providing 100mm space around the perimeter of the demonstrator to seal the vacuum bag against the tool surface. Laminate thicknesses are calculated using a cured ply thickness of 0.812mm, which was measured by inspecting the cross section of representative cured laminates made from the selected materials.

Table 14: Initial demonstrator structural dimensions.

Section	Dimension (mm)		Distance up tool surface from bottom edge of keel (mm)		Thickness (mm)			Foam Type
	Width	Length	Bottom of section	Top of section	Total section	Core	Skin	
Keel	2300	500	0	500	240	0	240	N/A
SP1	2300	3600	500	4100	240	200	20	GR200
SP2	2300	2620	4100	6720	119.2	100	9.6	GR135
SP3	2300	2480	6720	9100	79.2	60	9.6	GR135

3.8.1 Structural Transitions

Structural transitions are required between discrete sections of the hull shell. Figure 24 highlights how these transitions line up with the deck-to-shell joints, which will require additional structural support to effectively transfer load from the decks to the hull shell. It is therefore proposed that the structural transitions and joint supports be combined into a single set of features:

- Keel to SP1 interface
- Joint 1 support (SP1 to SP2 interface)
- Joint 2 support (SP2 to SP3 interface)
- Joint 3 support (top of SP3)

The purpose of this section is to swiftly identify feasible designs for each of the features listed above that satisfy the structural designers' requirements whilst also being manufacturable. The details of these features were therefore decided jointly between Airborne UK and DAMEN. This study primarily focuses on manufacturing challenges that were investigated by the author at Airborne UK, with DAMEN providing insight and feedback on whether the design is acceptable from a structural perspective. As this is a research project with high levels of manufacturing risk, it is important to note that the solutions presented here are not optimised designs, but rather feasible solutions that were identified using expert knowledge and prior experience.

Selection of suitable design features such as the joint supports and transitions is typically a complex process in which design iterations and manufacturing trials may be conducted to arrive at an optimised result. This was not possible within this project due to time and resource limitations, so the selection process was simplified to enable a more rapid development approach. Where possible, the selection and refinement of each design feature was split into two decisions; what type of transition should be used at each location, and what transition angle should be used at each location. Both decisions strongly influence the sectional properties and manufacturability of each feature. Selection of suitable types of design features is made below. Transition angles are determined separately for each feature in the following subsections.

> **Question:** What are the most suitable types of structural transitions for the demonstrator?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts and structural designers.

It is important to note that at this early stage, the evaluation of each option is based solely on expert opinion and prior experience. Experimental studies are required to gain a more complete understanding of the strengths and limitations of each option. However, due to the scale and quantity of materials required to conduct these trials, it was not possible to conduct dedicated, isolated experimental trials for each option. Simulation methods would be useful here to rapidly investigate a range of different processing options and should be considered in future work. Instead, it was decided that experimental learning would be gained during the demonstrator production. It was therefore decided that a range of different structural transition features should be incorporated within this demonstrator study, as to facilitate the exploration of as many different options as possible, and therefore maximise the learning gained during this research project. Thus, the purpose of this selection process is to identify where each type of feature is best suited within the demonstrator, ensuring that all designs feature at least once within the demonstrator. The following evaluation criteria were identified for the selection of suitable structural transitions:

- **Effect on structural performance:** A relative comparison of the estimated structural performance (local strength, stiffness) of each option. Factors such as laminate thickness (thick monolithic vs sandwich/thin plies) and fibre alignment along load paths are considered. Lower regions of the hull are more highly loaded compared to upper regions near the gunwale. Therefore, strength and stiffness are more important factors in these regions.
- **Manufacturability of local transition region:** A relative comparison of how easily each feature can be manufactured. This includes considerations such as how the feature is either preformed and positioned on the tool, or formed directly on the tool, for various locations across the tool surface.
- **Effect on manufacturability of entire hull shell/demonstrator:** A relative measure of how each design effects the manufacture of the entire demonstrator. This includes effects on global preform stability and the ease in which the inner and outer skin plies can be laid up over the transitions. The scale of the demonstrator, the presence of large vertical regions and the predicted long layup duration (2+ weeks) mean that the preform must be stable enough as not to deform or collapse under its own weight prior to application of a vacuum bag.

Three different types of transition/joint support designs are identified during round table discussions as being the most suitable for this case study. Further information on these concepts, including visual depictions and dimensions, are available in the latter sections of this selection process. All evaluation criteria were assigned the same weighting for this selection.

Table 15 Indicates that some designs are better suited to certain regions of the demonstrator than others. The greater rigidity and lack of thickness variation under vacuum of the pre-infused monolithic block make it best suited to regions lower down the demonstrator where weights and ply thicknesses are greater. The dry monolithic preforms are generally preferred from a structural performance perspective as there are fewer concerns over interface strength. However, if a dry monolithic preform is positioned between two rigid sandwich sections, the plies within the monolithic preform could buckle under the weight of the upper demonstrator preform, leading to local deformation and total preform collapse. Therefore, dry monolithic preforms are best suited to the extremities of the demonstrator (the keel and gunwale), where the monolithic preforms are not surrounded on both sides by rigid sandwich sections. However, further development is required to address the debulking issue linked to this design. Through-thickness shear ties are more applicable to the upper regions of the demonstrator where ply thicknesses are lower, due to the way in which these preforms must be formed.

Table 15: Comparison of different joint support designs

Evaluation Criteria	**Monolithic:** Pre-infused block placed within dry demonstrator preform. The demonstrator is then infused with resin, which bonds to the pre-infused block to create a continuous structure.	**Monolithic:** Dry preform, infused with demonstrator.	**Through-thickness shear ties with local foam core:** Dry preform, infused with demonstrator.
Effect on structural performance	Solid, monolithic region has high strength and stiffness. Quality/strength of bond between pre-cured block and adjacent co-infused sandwich regions is not known. Previous experience of this approach with other resin systems at Airborne UK indicate a good bond is possible.	Solid, monolithic region has high strength and stiffness. Infused simultaneously with the rest of the demonstrator preform, so no potential concerns over transitional bond quality/strength.	Local through-thickness shear ties provide additional local shear and through-thickness tensile strength and stiffness. Directional plies aligned more closely with load paths enables a more efficient design.
Manufacturability of local transition region	Part can be laid up and infused on an easily accessible flat surface separate from the demonstrator production. Requires an additional infusion step compared to dry preforms but allows for a more controlled infusion with lower risk of local defects. Pre-infused block is potentially very heavy and possibly difficult to position on demonstrator tool, especially for inclined regions further up the tool surface.	Large monolithic region must be infused as part of larger, more complex demonstrator preform, increasing infusion complexity and risk of local defects. It is difficult to layup/position large monolithic sections high up on the inclined/vertical regions of the demonstrator tool due to preform weight and access limitations.	Complex 3D dry preforms must be created that feature foam core sections wrapped with dry glass reinforcement. Thicker plies lead to greater risk of local fibre wrinkles (due to wrapping around corners of foam core). Therefore, this option is more applicable to upper regions of the demonstrator where ply thicknesses are reduced.
Effect on manufacturability of entire hull shell demonstrator	Solid, pre-infused block can support the weight of the upper demonstrator preform easily without local or global preform collapse. Pre-infused block also avoids debulking issue, allowing inner skin to be laid up smoothly over transition region.	Dry preform will buckle under excessive weight, potentially resulting in local or global preform collapse. Debulking is a key issue, resulting in a potential step transition in the inner skin between the monolithic preform (which changes thickness under vacuum) and adjacent foam core sections (which do not).	Foam core wrapped with glass reinforcement provides some local preform stability. This design does not experience as much of a thickness change under vacuum compared to dry monolithic preforms, therefore the debulking issue is less severe.
Total Score	7	6	6

The following design decisions are made based upon the evaluation of structural transitions:

- Keel to SP1 interface: **Monolithic:** Dry preform, infused with demonstrator.
- Joint 1 support (SP1 to SP2 interface): **Monolithic:** Pre-infused block placed within dry demonstrator preform.
- Joint 2 support (SP2 to SP3 interface): **Through-thickness shear ties with local foam core:** Dry preform, infused with demonstrator.
- Joint 3 support (top of SP3): **Monolithic:** Dry preform, infused with demonstrator.

The geometric details of each of these features are further refined in the following subsections below. The most critical decision is to determine the transition angle for each feature, as the rest of the dimensions are generally determined by the sectional dimensions of the demonstrator design outlined in Figure 24. The following evaluation criteria were identified for selecting a suitable structural transition angle for each feature. All criteria are given the same weighting.

- **Effect on structural performance:** Where possible, a sharp or sudden transition between two continuous regions should be avoided to minimise stress concentrations within the transition region which could lead to premature failure. A 30° taper (measured from tool local surface) was proposed by DAMEN based upon prior design and manufacturing experience with composite ship hulls (WP17, 2018). This angle provides a good compromise between manufacturability and local structural loading for smaller composite hulls. 30° is therefore set as the ideal taper angle for each of the features/structural transitions in the demonstrator. The transition taper angle of each design is used to compare the relative effect on structural performance for each option. The designs with transition angles closer to 30° are deemed to have greater structural performance than those closer to 90°. It is important to note that this is a simplified approach that was used to rapidly select a suitable design in the absence of detailed structural calculations for each option.
- **Manufacturability of local transition region:** A relative measure of how easily each option can be manufactured, focusing solely on the layup and infusion of materials within the local transition region. This includes the formation of pre-infused blocks and dry preforms, shaping foam core sheets and positioning these features on the tool surface.
- **Effect on manufacturability of entire hull shell/demonstrator:** A relative measure of how each design effects the manufacture of the entire demonstrator. This includes the effect of transition geometries on global preform stability and the ease in which the inner and outer skin plies can be laid up over the transitions. The scale of the demonstrator, the presence of large vertical regions and the predicted long layup duration (10 days, see Table 4) mean that the preform must be stable enough as not to deform or collapse under its own weight prior to application of a vacuum bag.

Only three transition angles are considered in this initial selection phase to enable a rapid evaluation and selection. These are described below and visually depicted in Table 16.

- **30° Transition**: As discussed previously, a 30° transition between discrete structural regions is preferred for structural design considerations. This should be used where possible throughout the demonstrator. However, additional considerations such as alignment of the transition with local loading and effect on preform stability should also be considered where appropriate.
- **150° Transition (inverted 30° transition):** This is essentially a mirrored version of the 30° transition and is therefore assumed to provide similar structural performance. Inverting the transition may influence the manufacturing procedure (i.e. ease of manufacture, cost, and risk of defects) and alignment of the transition joint with respect to local loading.
- **90° Transition:** Identified as being the easiest transition angle to manufacture, a 90° transition does not require any additional machining or forming stages, resulting in a faster and more

affordable manufacturing process. 90° transitions are also thought to be better than angled transitions regarding preform stability, however, this option may have a negative impact on structural performance due to the potential for stress concentrations and local weaknesses resulting from this sudden transition.

No other transition angles are considered in this initial evaluation. If none of the above options are suitable for a particular transition feature, then a customised transition angle is selected based upon the results of the evaluation and further analysis. The purpose of this initial selection phase is therefore to quickly identify for each feature if the preferred 30° transition (regular or inverted) is possible, or whether a 90° transition (or other angle) is required. Each transition is considered individually in the subsections below.

3.8.1.1 Keel to SP1 interface

The keel consists of 332 plies of glass stacked uniformly to form a solid monolithic laminate. Some of these plies continue up the part to form the inner and outer skin of the sandwich panels. All plies are laid up parallel to the local tool surface. The transition from the monolithic keel to the SP1 sandwich panel is located at the base of the demonstrator where the tool is horizontally oriented. Therefore, the effect of transition angle is thought to be less critical to the global preform stability compared to more vertically aligned regions of the demonstrator. On the other hand, the bulk factor of the monolithic region is considered to be a critical concern for this feature.

The previous debulking showed how the dry preformed laminate thickness will be reduced by up to 27% when vacuum compaction is applied. The trials also demonstrated how the material springs back to 90% of its original thickness when the vacuum compaction is removed, limiting the effectiveness of debulking procedures. This poses an issue at the keel/SP1 interface, where a sudden change in thickness between monolithic and foam core sandwich will likely result in large wrinkles within the inner skin. Figure 25 shows this potential issue. It is estimated that the monolithic thickness will reduce by approximately 54mm. An angled taper has been shown to significantly reduce this debulking effect by distributing the thickness change over a greater distance, thus preventing any large wrinkles from forming. Further details regarding the manufacture of this section and proof of this concept can be found in the demonstrator manufacture chapter.

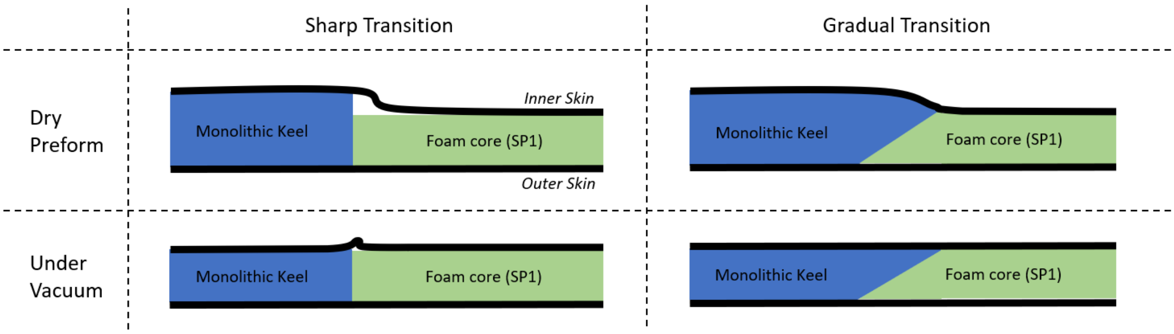


Figure 25: Skin wrinkling due to monolithic bulk factor

With this information, it is possible to evaluate each option against the previously defined criteria.

Table 16: Evaluation of different transition angles for Keel to SP1 interface

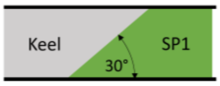
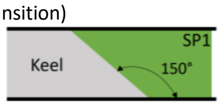
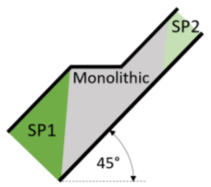
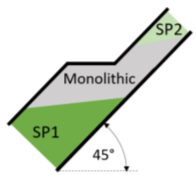
Evaluation Criteria *(weighting)*	**30° Transition** 	**150° Transition** (inverted 30° transition) 	**90° Transition** 
Effect on structural performance *(1)*	Considered to be optimal for this case study based upon expert opinion and prior experience.	Considered to be optimal for this case study based upon expert opinion and prior experience.	Could lead to high stress concentrations and local weaknesses.
Manufacturability of local transition region *(1)*	Tapered transition can be created by shaping foam core and staggering plies. Positioning the monolithic section on top of the foam should allow easier layup and positioning of plies, as the machined foam core taper acts as a guide/datum. Furthermore, the heavier monolithic section should "clamp" the foam in position and create a more robust preform.	Tapered transition can be created by shaping foam core and staggering plies. Positioning the foam core on top may lead to a less uniform transition as plies may not fully align with machined foam core edge. There is also a risk of the foam core moving during demonstrator layup as it is not tightly held down.	Transition can be created with no additional ply staggering or foam core machining tasks.
Effect on manufacturability of entire hull shell demonstrator *(1)*	Region of demonstrator at the keel/SP1 interface is horizontally oriented with some weight from upper preform being carried through the transition. A tapered transition is possible here without preform collapse. Furthermore, a tapered transition will alleviate the debulking issue (see Figure 25).	Region of demonstrator at the keel/SP1 interface is horizontally oriented with some weight from upper preform being carried through the transition. A tapered transition is possible here without preform collapse. However, this taper orientation would likely not alleviate the sudden thickness transition due to bulk factor.	Sudden transition will result in thickness change due to monolithic compaction under vacuum. This may lead to large wrinkles in the inner skin laminate.
Total Score	**8**	**6**	**6**

Table 16 indicates that a 30° transition is the most suitable option for the Keel to SP1 interface. The design schematic for this feature is shown in Figure 26A.

3.8.1.2 Joint 1 Support

This feature is positioned approximately 2m up from ground level and inclined at 45° relative to the ground. A pre-infused monolithic region was selected for this transition. To reduce manufacturing complexity, the monolithic block is manufactured so that all plies are oriented parallel to the local demonstrator tool surface (i.e., no 3D or through-thickness aligned fibres). The selection of a pre-infused section means that the bulk factor issue is not a concern for this feature. However, the approximate 45° inclination of this region and its position near the base of the demonstrator mean that its geometry will have a critical impact on the overall stability of the demonstrator preform.

Table 17: Evaluation of different transition angles for Joint 1 support

Evaluation Criteria *(weighting)*	**30° Transition** 	**150° Transition** (inverted 30° transition) 	**90° Transition** 
Effect on structural performance *(1)*	30° local taper previously identified as preferred transition for structural performance.	30° local taper previously identified as preferred transition for structural performance.	Sudden transition could lead to high stress concentrations and local weaknesses.
Manufacturability of local transition region *(1)*	Tapered transition can be created by shaping foam core and staggering plies. Creating a tapered edge on the pre-infused monolithic block that closely matches the SP1 taper could be difficult in practice. Lifting the heavy pre-infused monolithic block into position behind the SP1 taper could also be challenging.	Tapered transition can be created by shaping foam core and staggering plies. Creating a tapered edge on the pre-infused monolithic block that closely matches the SP1 taper could be difficult in practice. Lifting this monolithic block into position is thought to be less challenging than for the 30° transition	Transition can be created with no additional ply staggering or foam core machining tasks.
Effect on manufacturability of entire hull shell demonstrator *(1)*	Any transition angle in this region is thought to lead to instability. The weight of the upper demonstrator preform may cause the 30° tapered monolithic section to push the SP1 sandwich preform away from the tool surface, resulting in preform deformation and/or collapse.	Any transition angle in this region is thought to lead to instability. The weight of the upper demonstrator preform may cause the 150° tapered monolithic section to slip over the SP1 tapered edge, leading to collapse of the upper demonstrator preform.	Pre-infused block will alleviate any debulking issues. A 90° transition will provide a sturdy platform to support the weight of the upper demonstrator preform.
Total Score	**6**	**5**	**7**

A 90° transition was identified as being the most suitable transition angle for this feature, primarily due to stability concerns at this inclined region of the demonstrator. A 90° transition is considered to be the lowest manufacturing risk approach and is therefore selected on this basis. DAMEN accepted this transition angle despite its potential negative effect on structural performance. It should be noted that a transition angle between 90° and 30° may be possible, however numerous large-scale manufacturing trials must be conducted to determine a suitable value. This would require a large quantity of materials, time and resources which are not available within this study. Optimisation of this transition angle is therefore left for future work. The proposed design schematic for the joint 1 support is displayed in Figure 26B.

3.8.1.3 Joint 2 Support

This feature is positioned approximately 4m up from ground level and inclined at 75° relative to the ground. A shear-tie feature was previously selected for this transition as it is easier to create this feature on elevated and inclined tool surface compared to a thick monolithic section. Refinement of this transition is far more complicated that previous design features due to the greater number of design variables. In addition to transition angle, factors such as the number and position of shear ties, number of plies and stacking sequence and type of foam core that is used must all be determined. For this reason, the previous evaluation matrix methodology is not applicable here. Instead, in the absence of structural calculation iterations and extensive manufacturing trials, the details of this transition were determined during a round-table discussion using expert opinion and prior experience in both composites design and manufacture. It is important to note that an optimised design is not required for this study, and thus generation of a feasible design using this approach is satisfactory. Further work is suggested to optimise the design of this feature in future design iterations. An explanation of the chosen design and justification of the decisions made are presented below.

The final geometry for the joint 2 support detail is displayed in Figure 26C. The primary constraint of this geometry was the request from designers to incorporate a horizontal ledge at joint 2 to support the deck. As joint 2 is inclined at approximately 75° in relation to the ground, forming a horizontal step at this location would require two geometric transitions, both with angles of 75° (see yellow line on Figure 26C). The difference in sectional thickness between SP2 and SP3 is approximately 40mm. Therefore, these sharp geometric transitions will be only 40mm apart. Laying up the 14mm thick inner skin laminate over these closely positioned transitions will likely result in significant levels of fibre wrinkling. It was therefore decided to incorporate a more gradual structural transition between SP2 and SP3, and layup a small monolithic preform over the inner skin to provide the desired horizontal step. The grey region in Figure 26C shows this monolithic support.

The design features two shear ties that are positioned at the start and end of the geometric transition between SP2 and SP3. These positions were selected to provide additional structural support at the two locations where the inner skin bends around the geometry. The shear ties provide a direct load path from the inner to outer skin, distributing the load from deck 2 throughout the hull shell structure. The shear ties are constructed using the same layup/stacking sequence as the inner and outer skins in SP2 & 3 to allow for an even distribution of load between the inner and outer skins. The shear ties are oriented at 45° in relation to the local tool surface, as this was thought to be the best compromise between structural performance and preform stability. A higher density foam core (GR200) is positioned between the two shear ties to provide additional support underneath the deck 2 joint.

GR200 was chosen as it is the highest density foam core of those selected for this case study. The designers working on the joint details also requested a horizontal ledge to support the deck joint. This results in a sharp transition in sectional thickness which would lead to fibre wrinkles and bridging within the inner skin. To avoid this, it is proposed that a smooth transition be implemented across the feature, with a secondary monolithic support added over the inner skin to provide the required geometry. The proposed design schematic for the joint 2 support is displayed in Figure 26C. The shear ties are positioned beneath joint 2 to better support the local loads.

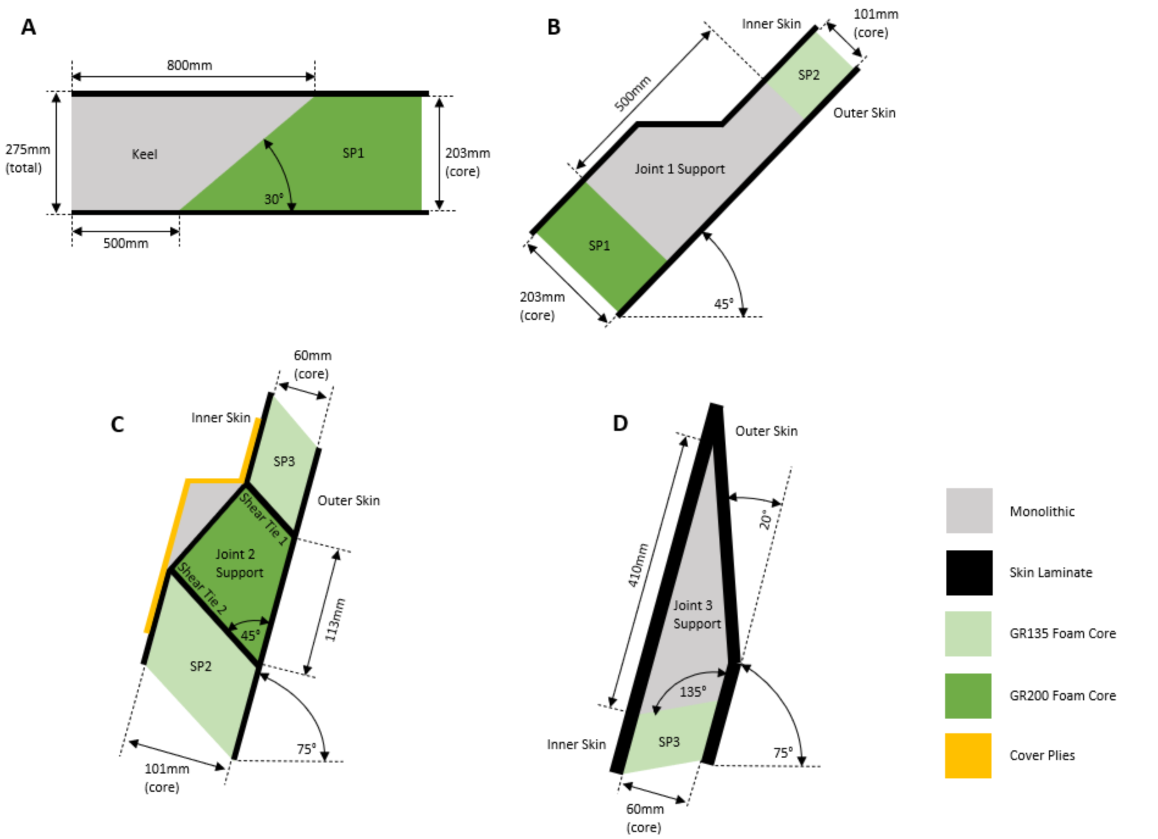


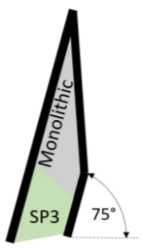
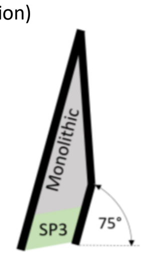
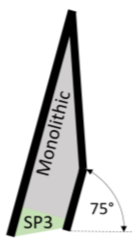
Figure 26: Design schematic for structural transitions and joint supports

3.8.1.4 Joint 3 Support

This feature is located at the top of the demonstrator. A monolithic region was previously selected for this transition. The top deck is joined to the hull shell via a large lap bond located on the outer skin. The top region of the hull shell should be tapered to facilitate transfer of loading between the hull and deck. A 20° taper was proposed for this hull-deck shear lap joint based upon previous designs and round-table discussions with designers and manufacturers. The transition angle between this monolithic region and SP3 was determined based upon the evaluation presented in Table 18.

The total scores presented in Table 18 indicate that a 150° taper is the most suitable of the three options considered. However, there are still some concerns with this option regarding local preform stability as there is a risk of the monolithic preform slipping downwards over the taper due to the local vertical orientation. To reduce the risk of this happening, it was decided that the taper angle be reduced to 135°. This decision was made based upon expert opinion and prior manufacturing experience with thick monolithic laminates. If required, this angle would be modified further to better accommodate the manufacturing process if required during experimental trials and/or demonstrator manufacture. The proposed design schematic for the joint 3 support is displayed in Figure 26D.

Table 18: Comparison of joint 3 support designs

Evaluation Criteria	**30° Transition** 	**150° Transition** (inverted 30° transition) 	**90° Transition** 
Effect on structural performance	The upper deck loading is assumed to act vertically downwards. A 30° taper in this orientation will align the transition more closely with the load path, which may result in higher shear stresses.	Considered to be optimal for this case study based upon expert opinion and prior experience. Taper is not aligned closely to the load path, resulting in lower shear loading across this transition.	Could lead to high stress concentrations and local weaknesses.
Manufacturability of local transition region	Tapered transition can be created by shaping foam core and staggering plies. Monolithic preform is positioned between foam taper and tool surface, preventing the monolithic preform sliding downwards. However, there is a risk that the weight of the monolithic preform will push the foam taper away from the tool.	Tapered transition can be created by shaping foam core and staggering plies within monolithic region. There is a risk of the monolithic preform sliding down the tool due to the vertical inclination and orientation of the foam taper.	Transition can be created with no additional ply staggering or foam core machining tasks. The 90° foam edge supports the weight of the monolithic preform and restrains local movement.
Effect on manufacturability of entire hull shell demonstrator	This feature is located at the top of the demonstrator preform, and therefore does not act as a support for any other region. Local stability/integrity will have no effect on the rest of the demonstrator. Local taper reduces severity of monolithic debulking issue.	This feature is located at the top of the demonstrator preform, and therefore does not act as a support for any other region. Local stability/integrity will have no effect on the rest of the demonstrator. Local taper reduces severity of monolithic debulking issue.	This feature is located at the top of the demonstrator preform, and therefore does not act as a support for any other region. Local stability/integrity will have no effect on the rest of the demonstrator. Wrinkles may form within the inner skin due to monolithic bulk factor.
Total Score	7	8	6

3.8.2 Inclusion of flow media

The hull shell features thick laminates which would be difficult to infuse by conventional means. The benefits of flow media for infusing thick laminates were introduced in the material selection stage of this work. It was already decided that flow media shall be used in this case study, and a suitable material has already been selected. Therefore, only one research question relating to the use of flow media remains unanswered:

> **Question:** How many flow media plies should feature in the laminates of the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts and structural designers.

It was previously discussed how flow media leads to a slight reduction in in-plane laminate properties. This assumes that some structural reinforcement plies are replaced with flow media. To ensure that the properties of the laminates within the demonstrator are not compromised, it is proposed that the flow media is added as extra plies to the stacking sequence. This results in a slightly thicker, stiffer, and heavier laminate than specified in the original design, although the manufacturability is significantly improved without compromising the overall strength of the structure.

Identification of a suitable number of flow media plies is a potentially complex compromise between structural performance and manufacturability. This decision was made based upon expert experience to enable a rapid, but informed choice to be made in the absence of extensive experimentation and design iterations. Airborne UK has prior experience using flow media in other commercial projects, and this knowledge was captured and summarised in the following evaluation matrix (Table 19). The following evaluation criteria were identified for this selection:

- **Structural weight:** For the purposes of this manufacturing study, flow media plies are assumed to be resin rich layers due to their large flow channels and far lower fibre volume fraction compared with the quadaxial reinforcement. As previously mentioned, flow media plies will not replace existing quadaxial plies within structural laminates in this study. Instead, additional flow media plies will be added to improve resin flow. In doing this, we are essentially adding additional resin rich layers within the laminate which will increase the total structural weight. Because no quadaxial plies are removed, it is assumed that the addition of flow media plies results in laminates that are at least as strong and stiff as the initial structural iteration provided by DAMEN.
- **Resin infusion:** Flow media improves resin flow, providing faster infusions with the potential for improved resin-wet out and reduced voidage. More flow media plies will result in faster infusions.

- **Layup:** A single type of universal quadaxial reinforcement was selected to reduce layup complexity. Incorporating more flow media plies may result in greater layup complexity and duration, as rolls of flow media and quadaxial reinforcement would need to be switched over more regularly during the process. Quadaxial plies are also thought to be easier to layup onto the vertical regions of the tool compared to Saerflow, based upon prior experience using these materials at Airborne UK.

Three different frequencies of Saerflow were considered in this decision that are based upon prior experience and manufacturer's recommendations.

Table 19: Evaluation of different frequencies of flow media within structural laminates for the selected case study

Evaluation Criteria *(weighting)*	1 Saerflow ply every 20 Quadaxial plies	1 Saerflow ply every 10 Quadaxial plies	1 Saerflow ply every 5 Quadaxial plies
Structural weight *(1)*	Fewer flow media plies will have little effect on total structural mass.	Incorporating some flow media plies will slightly increase the structural mass.	More flow media plies result in greater total structural mass.
Resin Infusion *(3)*	Fewer flow media plies result in a slower infusion, and potentially worse resin wet-out.	Incorporating some flow media plies results in a sufficiently fast resin flow rate for large infusions of this scale.	More flow media plies result in a faster infusion, and potentially worse resin wet-out.
Layup *(2)*	Fewer flow media plies result in a more streamlined layup process.	Incorporating some flow media plies results in some additional layup complexity.	More flow media plies result in a more complex layup process where materials must be switched more often.
Total Score	**12**	**12**	**12**

Table 19 indicates that there is no clear best choice. 1 Saerflow every 10 Quadaxial was ultimately selected as it provides an even compromise between structural performance and manufacturability. DAMEN deemed this frequency of flow media acceptable for their structural design. This frequency of Saerflow will act as a universal goal for all laminates within the hull shell demonstrator, however this may be modified slightly on an individual basis to ensure laminate balance and symmetry.

3.8.3 Ply drops

There are two transition regions within the demonstrator where ply drops are required. The first region is the structural transition between SP1 and SP2, as indicated by the thickness change of the skin laminates in Table 14. The second transition region is at the keel. The addition of flow media plies in this region increases the total thickness of the monolithic laminate. This results in a monolithic keel that is considerably thicker (~30mm) than the adjacent SP1 section. This sudden change in thickness is unacceptable as it will result in wrinkles and other local defects which do not meet the previously defined defect acceptance criteria. To address this issue, 35 plies were removed from the monolithic core and relocated into the inner and outer skins. These plies end shortly after the keel/SP1 transition, utilising a series of ply drops within the laminate skins.

These two-ply drop transitions divide the demonstrator into three discrete regions. Therefore, plies within the inner and outer skin laminates can be categorised based upon which regions they are located within. Figure 29 shows these ply groups, which are referred to as short, medium, and long.

The ply drops featured in this structure must be sufficiently spaced as not to create local structural weaknesses. The key research question that must be answered is:

> **Question:** What is a suitable ply drop spacing for the structural laminates in the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts and structural designers.

An evaluation matrix was not deemed a suitable approach for this decision as it is difficult to compare quantitative ply drop spacing values in a qualitative manner without extensive structural calculations. To avoid the need for structural calculation iterations, a decision was made based upon ply drop spacings used in previous commercial projects and the predicted realistic ply layup tolerances for this specific case study.

During round-table discussion with experts, a ply drop spacing of 10 times the ply drop thickness was identified as a common rule-of-thumb to reduce stress concentrations within marine composite laminates. Ply drop spacings smaller than this are thought to generate unacceptable stress concentrations. Other sources indicate a ply-drop spacing of between 10 and 20 times the ply drop thickness is appropriate for structural laminates within aircraft structures (Farrow, 2011) (He, K., et al., 2000). It appears that this rule-of-thumb has been passed down from the aerospace to marine industry. Investigating the full extent to which this rule-of-thumb is applicable to large marine structures is beyond the scope of this work. In the absence of detailed theoretical predictions and experimentation, a ply drop spacing equal to 20 times the ply thickness was selected as a conservative minimum value to be applied throughout this case study. For an average cured ply thickness of 1mm, this equates to a ply drop spacing of 20mm. However, it is also important to consider manufacturing tolerances when determining whether this ply drop spacing is suitable for this case study.

+/-30mm was determined to be the worst-case variation in longitudinal (from keel to gunwale) ply positioning based upon expert opinion and prior experience. This large positioning tolerance is primarily due to the handling of large plies, part curvature and limited access to the tool surface. It is important to note that this is an estimate based upon prior experience before full-scale experimental trials were conducted. Combining this positioning tolerance with the minimum ply drop spacing previously selected (20mm) results in a conservative ply drop spacing of 80mm that accounts for stress concentrations and manufacturing variability. It is important to note that this conservative approach to ply drop spacing results in longer transitions between laminate thicknesses, which ultimately increases material usage, production cost and structural weight.

Ply drops shall be positioned within the laminate as per standard Airborne UK procedures for composite structures. Ply drops shall be evenly dispersed throughout the thickness of the laminate, with no ply drops located adjacent to one another. Ply drops shall also be surrounded either side by continuous plies to restrain peel stresses.

3.8.4 Ply staggering

The glass reinforcement selected for the manufacture of the demonstrator is supplied in 1.27m wide rolls. However, the demonstrator is 2.3m wide, so multiple plies of the reinforcement must be joined together in the width direction to create this structure. The joints between these sub-plies must be staggered to avoid continuous resin rich regions through the thickness of the structure, which could lead to cracks (which are defined as unacceptable within the specification). To do this, a ply pattern must be generated that details where each ply is positioned on the tool relative to one another.

It is important to note that glass reinforcement is available in 2.5m wide rolls, which would immediately solve this issue if used in this case study. The 1.27m wide rolls were deliberately selected because this manufacturing challenge also exists within the full scale 75m long hull shell (as 75m wide rolls of reinforcement are not commercially available or practical).

Two research questions are identified which relate to identification of a suitable ply pattern and acceptable lateral ply spacing.

> **Question:** What is a suitable ply layup pattern for the structural laminates in the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts and structural designers, using publicly available guidelines where available.

Ply splice joints are formed following the Airborne UK standard procedures for ply drops which were previously discussed; no ply splice joints may be located adjacent to one another, and each ply splice joint shall be surrounded either side by continuous plies to restrain peel stresses.

Universal design guidelines were used to make an informed and rapid decision in the absence of detailed structural calculations that model localised stress concentrations around these features at the ply level. Aerospace design guidelines are used as a conservative reference in the absence of equivalent publicly available guidelines for large composite marine structures. The following guidelines for ply splice joints are outlined in the Department of Defence Handbook for Composite Materials based upon lessons learned in the aerospace industry (United States of America Department of Defense, 2002). The guidelines are focused toward composite materials typically used in aerospace applications.

Table 20: Relevant aerospace guidelines for ply splice joints

<table>
<tr><td>Design Guideline*</td><td>Reason*</td><td>Applicability to case study manufacture</td></tr>
<tr><td>A continuous ply should not be butt spliced transverse to the load direction.</td><td>Introduces a weak spot in the load path.</td><td rowspan="2">Primary load path in demonstrator is assumed to be along circumferential length based upon requirement in project specification for continuous fibres along this direction. Splice joints in width direction are therefore acceptable based upon this guideline. Separation of splice joints with 4 continuous plies may significantly increase manufacturing complexity, and so applicability should be reviewed. Separate from the demonstrator, the applicability of these splice joints should be reviewed when considering load paths within the full 75m long hull shell structure.</td></tr>
<tr><td>A continuous ply may be butt-spliced parallel to the load direction if coincident splices are separated by at least four plies of any orientation.</td><td>Eliminates the possibility of a weak spot where plies are butted together.</td></tr>
<tr><td>The butt joint of plies of the same orientation separated by less than four plies of any direction must be staggered by at least 0.6 inch (15 mm).</td><td>Minimizes the weak spot where plies are butted together.</td><td>This guideline is in close agreement with Airborne UK standard procedure. As previously stated, alignment of ply splice joints should be avoided to ensure defect acceptance criteria are met. A 15mm minimum stagger is easily achievable in this case study.</td></tr>
<tr><td>Overlaps of plies are not permitted. Gaps should not exceed 0.08 inch (2 mm).</td><td>Plies will bridge a gap but must joggle over an overlap.</td><td>Overlapped plies result in a greater risk of fibre wrinkles which may exceed acceptance criteria. Furthermore, the demonstrator features thick monolithic laminates which will exacerbate this issue. A 2mm maximum gap may not be achievable based upon estimated ply positioning tolerances.</td></tr>
</table>

Information extracted from Department of Defence Handbook for Composite Materials. Applicability to case study is author's contribution, with **areas for further review highlighted in bold.*

These guidelines appear to be mostly applicable to the manufacture of the selected case study. Two areas for further discussion are highlighted in Table 20 and discussed in further detail below.

The guideline for separating splice joints between 4 continuous plies is indeed possible for the production of the demonstrator and 75m hull shell. Implementing this guideline within the manufacture of the 75m hull shell is thought to have minimal impact on the complexity of the layup process, as identical plies can be offset laterally throughout the stacking sequence to achieve the desired distribution of staggered ply splice joints. However, implementing this guideline within the demonstrator manufacture will add considerable complexity to an already complex and novel manufacturing challenge. This is because plies cannot simply be offset over the majority of the demonstrator due to its limited width (2.3m). Instead, plies must be cut to specific widths to fit within the demonstrator. The greater the separation of splice joints within the stacking sequence, the greater the number of unique splice positions that are required, thus increasing the number of unique ply widths that must be cut. Cutting the plies along the width direction increases layup time and material wastage, both leading to greater production costs. Due to the high risk associated with this manufacturing project, it is preferred that the layup remains as simple as possible for this initial demonstrator production.

To reduce layup complexity, it was decided that a ply pattern be generated that resulted in the minimal amount of ply cutting, whilst also meeting all guidelines in Table 20, except those previously highlighted in bold. It is important to note that this decision is only relevant to the one-off demonstrator. It is suggested that the guideline for a 4-ply splice separation be followed for the 75m hull shell. The ply pattern for the laminates in the demonstrator, which was accepted by DAMEN, is shown in Figure 27.

A repeating pattern of four different ply combinations was determined to be the minimum number required to prevent any alignment of ply joints throughout the demonstrator. Plies are divided into "sub-plies". Multiple sub-plies are spliced together to form plies. Sub-plies are laid onto the tool in the following order: 1a, 1b, 2a, 2b, 2c, 3a, 3b, 4a, 4b etc… This 4-ply pattern is repeated throughout the stacking sequence for all 332 plies. The widths of the sub-plies (displayed in Table 21) are chosen in such a way to distribute the ply splice joints across the width of the demonstrator. The minimum spacing between splice joints in the width direction is 380mm, and no two splice joints are ever positioned adjacent to one another. Figure 27 also shows how this pattern accommodates the ply drop transition between SP1 and SP2. At this transition plies 1 and 3 are dropped, however the remaining ply splice joints in plies 2 and 4 do not align.

This pattern does not meet the previously identified guideline for ply splice joint separation (4 plies). Splice joints in SP1 are separated by 3 plies, whilst within SP2 & 3 only a single ply separates splice joints in the stacking sequence. As previously mentioned, this can be avoided in the full scale 75m hull shell by staggering the position of plies and is therefore a unique feature of this one-off demonstrator. This ply pattern was combined with the previously defined ply drops to generate full geometries for every ply. This can be found within Appendix A.1.

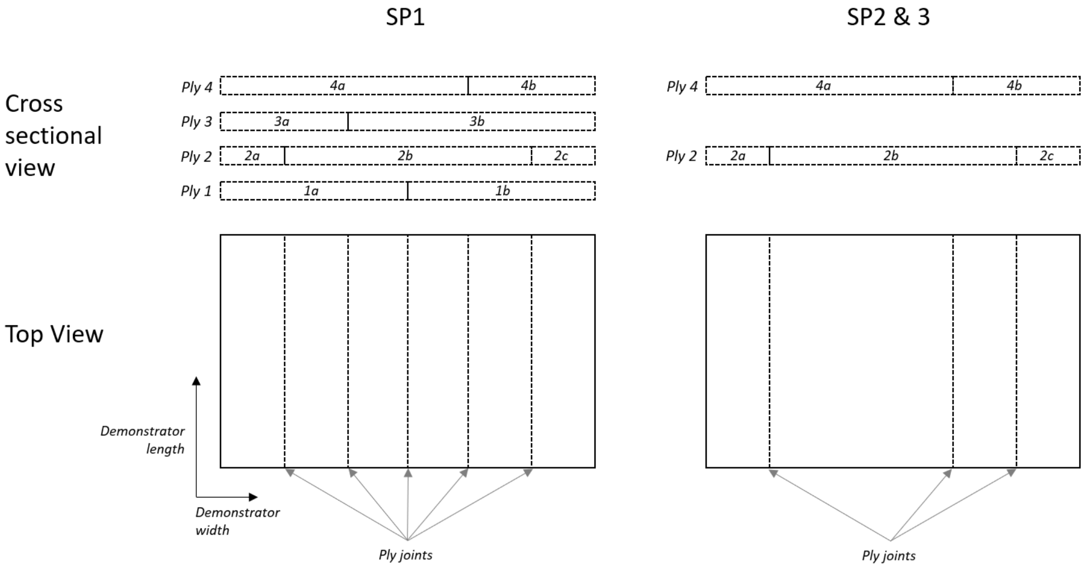


Figure 27: Ply pattern to stagger ply joints across width of demonstrator

Table 21: Sub-ply widths corresponding to ply pattern.

Ply I.D.	Sub-ply widths (mm)			Total ply width (mm)
	a	b	c	
Ply 4	1270	1030	N/A	2300
Ply 3	1030	1270	N/A	2300
Ply 2	515	1270	515	2300
Ply 1	1150	1150	N/A	2300

Having identified a suitable ply pattern for the laminate skin layup, one final research question remains:

> **Question:** What is a suitable gap between two plies at ply splice joints within structural laminates featured in the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts and structural designers, using publicly available guidelines where available.

The previously identified guideline suggests an acceptable gap of no greater than 2mm. This does not seem appropriate for this manufacturing study considering realistic ply positioning tolerances. In the previous section, a worst-case longitudinal ply positioning tolerance of +/-30mm was identified. However, when considering the ply splice joints, it is the lateral (width-wise) ply positioning tolerance that is most important. During a structured round-table discussion with manufacturing experts, a worst-case lateral ply positioning tolerance of +/-10mm was determined for the demonstrator manufacture. The following reasons are given as to why this is much smaller than the longitudinal positioning tolerance:

- Due to the vertical inclination of the upper tool surface, plies may have a tendency to slip downwards (in the longitudinal direction) under gravity. The plies are not expected to shift in the lateral direction during layup.
- The majority of plies are long (up to 9m in the longitudinal direction) and narrow (up to 1.2m in the lateral direction). The greater longitudinal length means plies can be more easily aligned with the edge of the demonstrator and/or adjacent plies. This provides the laminator with visual datums over the longest dimension of the plies, which may help reduce positional variation. Furthermore, the laminators can clearly see the gaps between ply splice joints and can therefore adjust the ply position during the layup process if necessary.

There is no direct reference to an acceptable gap between plies within the defect acceptance criteria presented in the initial specification. It is assumed that any gap between plies would be filled with resin during the infusion process, so the most relevant acceptance criteria are resin pockets (max diameter 6.5mm) and resin-rich edge (max 0.8mm from edge). Both values are smaller than the lateral layup positioning tolerance of +/-10mm.

Unlike with ply drop spacing, it is not possible in this case to rapidly select an appropriate ply gap value that is conservative with respect to both structural design and manufacturing tolerances. In the absence of detailed structural modelling, it was decided that the +/-10mm tolerance be used as an initial value for ply gaps at splice joints within the laminate (i.e., a gap between 0-20mm). This would be reviewed at a later stage during the demonstrator production when this positioning tolerance could be verified. It is important to note that the primary purpose of this novel research project is to understand what is feasibly possible/manufacturable in a shipyard. Therefore, applicability of acceptable geometries, tolerances and defects shall be continually reviewed. If there is insufficient confidence in the currently available knowledge/understanding, a fixed tolerance will not be set until further learning is gained during manufacturing trials.

The lateral ply positioning tolerance of +/-10mm is used to provide a preliminary goal for ply alignment tolerance relative to the edge of the demonstrator tool along the circumferential length. This tolerance results in a potential maximum ply position deviation of 20mm between the top and bottom of the demonstrator, which has a circumferential length of 9100mm. This equates to a maximum ply angle deviation of 0.13°. This value is clearly too small to detect via standard visual inspection procedures and is therefore not a practical tolerance to apply to the part. Instead, it is proposed that ply alignment be controlled by imposing the +/-10mm positioning tolerance to all plies relative to the edges of the demonstrator tool, as this is an easily measurable quantity.

3.8.5 Foam core layup pattern

The foam core is supplied as panels of 1000x1200x50mm in width, length and thickness respectively. As with the glass plies, these panels must be joined to create the 2.3m wide preform. The core primarily carries shear and compressive loads within the sandwich structure, so large discontinuities within the core should be avoided, as these may create local weaknesses and lead to premature failure. A foam panel pattern must be generated to achieve this.

> **Question:** What is a suitable foam sheet layup pattern for the sandwich regions in the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts.

None of the previously defined defect acceptance criteria are directly relatable to the creation of a suitable foam core pattern. Criteria for acceptable dry spots and resin rich areas are defined, however these are specific to structural laminates and rely on visual inspection for detection/acceptance.

The lack of stringent requirements for this region meant that there was no strong reasoning to deviate from common industry practice. The foam layup pattern was therefore based upon foam staggering approaches currently used in boatbuilding and wind turbine blade manufacture. This information was gathered during discussion with manufacturing experts.

Sandwich cores in boats are commonly formed by laying up preformed blocks/sheets onto the tool to form a single core layer. Foam kits are generated to achieve this, which consist of numerous pre-machined foam pieces that are assigned a predetermined position on the tool. The geometries of these sheets and the overall layup patterns vary depending on the size, shape, and design of the hull. A similar sandwich core layup process appears to be used in wind turbine blade manufacture (DTU, 2018). A similar kitting approach is proposed for this case study.

Sandwich regions of composite boats are typically much thinner than those featured in this case study, so a single layer of foam can be used achieve the desired thickness whilst maintaining the ability to drape around the curvature. The thicker the foam core, the greater the stiffness, and hence the more difficult it is to drape around curvatures. The discussion with experts indicated that 50mm was a common thickness that (with grooves and cuts) could drape around typical boat hull curvatures without breaking the foam or bridging the geometry. Based on this prior experience, 50mm thick foam sheets were selected for this case study to minimise manufacturing cost and risk. The increased thickness of the case study compared to conventional boat hulls meant multiple layers of foam core would be required. 4 layers of 50mm foam core were selected for the 200mm thick SP1 region, 2 layers of 50mm core were selected for the 100mm thick SP2 region, and 1 layer of 60mm foam core was selected for the 60mm thick SP3 region. In regions where multiple foam layers are used, the different layers should be staggered in relation to one another to avoid large through-thickness seams.

Figure 28 shows the author's proposed foam layup pattern. Reducing manufacturing complexity was a key driver behind this work. This pattern is thought to be the simplest solution to avoid large, continuous seams through the core thickness that span the width and/or length of the demonstrator. This is achieved by staggering the foam blocks relative to the previous row. This solution required minimal foam machining and cutting, using standard panel geometries where possible.

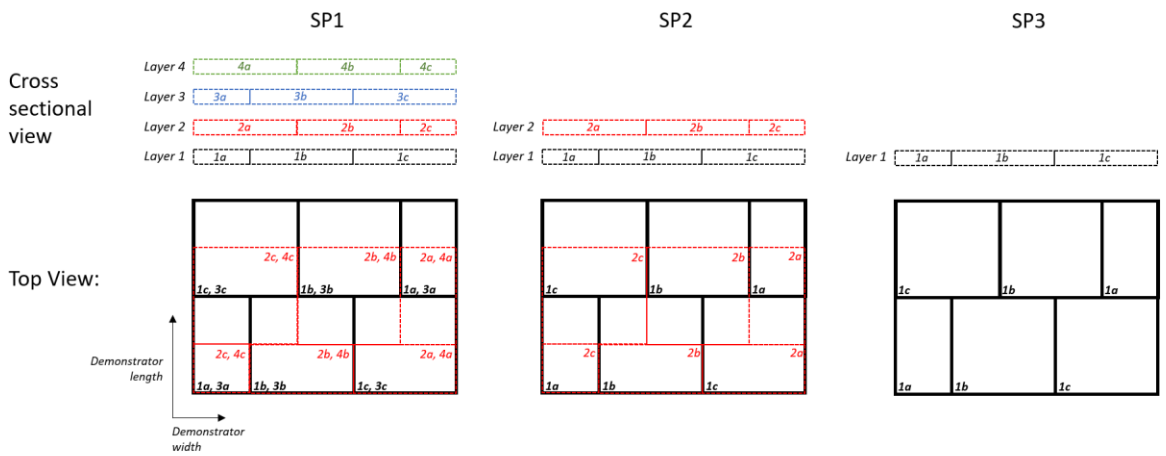


Figure 28: Foam panel layup pattern

The gaps between the foam core sheets are an additional detail that must be considered. To determine what a suitable gap between foam sheets would be for this case study, one must consider the previously defined list of acceptable defects and realistic manufacturing tolerances.

> **Question:** What is a suitable gap between two foam panels (in any direction) within sandwich regions featured in the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with manufacturing experts and structural designers.

Core sheets are typically laid up by hand in boatbuilding projects. Hull geometries (i.e., single and double curvatures, horizontal and vertical regions, and somewhat limited access to some regions) mean it is difficult to achieve perfect connections between foam pieces. Furthermore, foam pieces may move slightly during the hand layup procedure due to the size and weight of the preform and the geometry of the hull shell. An acceptable value for the gap between foam sheets is not provided in the project specification or defect acceptance criteria. Furthermore, a specific value for positional tolerances is difficult to find these are generally company/project specific. A maximum gap of 2mm between foam panels in featured in wind turbine blade preforms to avoid large resin channels and resin race-tracking (Composites World, 2020). However, there are some key differences between wind turbine blades and the hull shell case study which may increase the risk of dry regions (and thus potentially large divides/discontinuities) forming between core sheets within the sandwich core:

- The sandwich regions featured in this case study are much thicker than conventional sandwich structures featured in boats and wind turbine blades. The resin must travel further into the preform to fully penetrate the thick sandwich regions.
- The decision to divide the thicker foam core regions into multiple thinner layers results in far more gaps between foam pieces, some of which are located deep within the centre of the sandwich core.
- Through-thickness perforations in each foam sheet may not align with perforations in adjacent foam sheets, so there may not be sufficient resin flow pathways into the centre of the sandwich core.
- Variation in foam layup positioning (by hand) will lead to some gaps being larger than others. Larger gaps may promote resin flow, but smaller gaps where foam panels are tightly packed together may not see sufficient resin flow, resulting in disconnected foam sheets.

Therefore, for this case study we cannot assume with a sufficient level of confidence that all gaps between foam panels will fill with resin. To address this, it is proposed that a single ply of flow media be placed between adjacent foam panels to create controlled and consistent resin flow pathways. This approach is discussed in further detail in Section 5.6.3. This results in a minimum gap between foam panels of 1mm (the thickness of 1 flow media ply), which is comparable in magnitude to the 2mm gap in wind turbine blades. A maximum gap shall be identified during the demonstrator manufacture, during which the author can identify a realistic positioning tolerance first-hand.

3.8.6 Final Design

Figure 29 shows the final design schematic for the demonstrator section and Table 22 outlines the revised demonstrator dimensions. A ply book was also generated to describe the size and location of every ply that must be laid up onto the tool. This forms the basis of the methods manual that describes the demonstrator manufacture procedure. The ply book can be found in Appendix A.1.

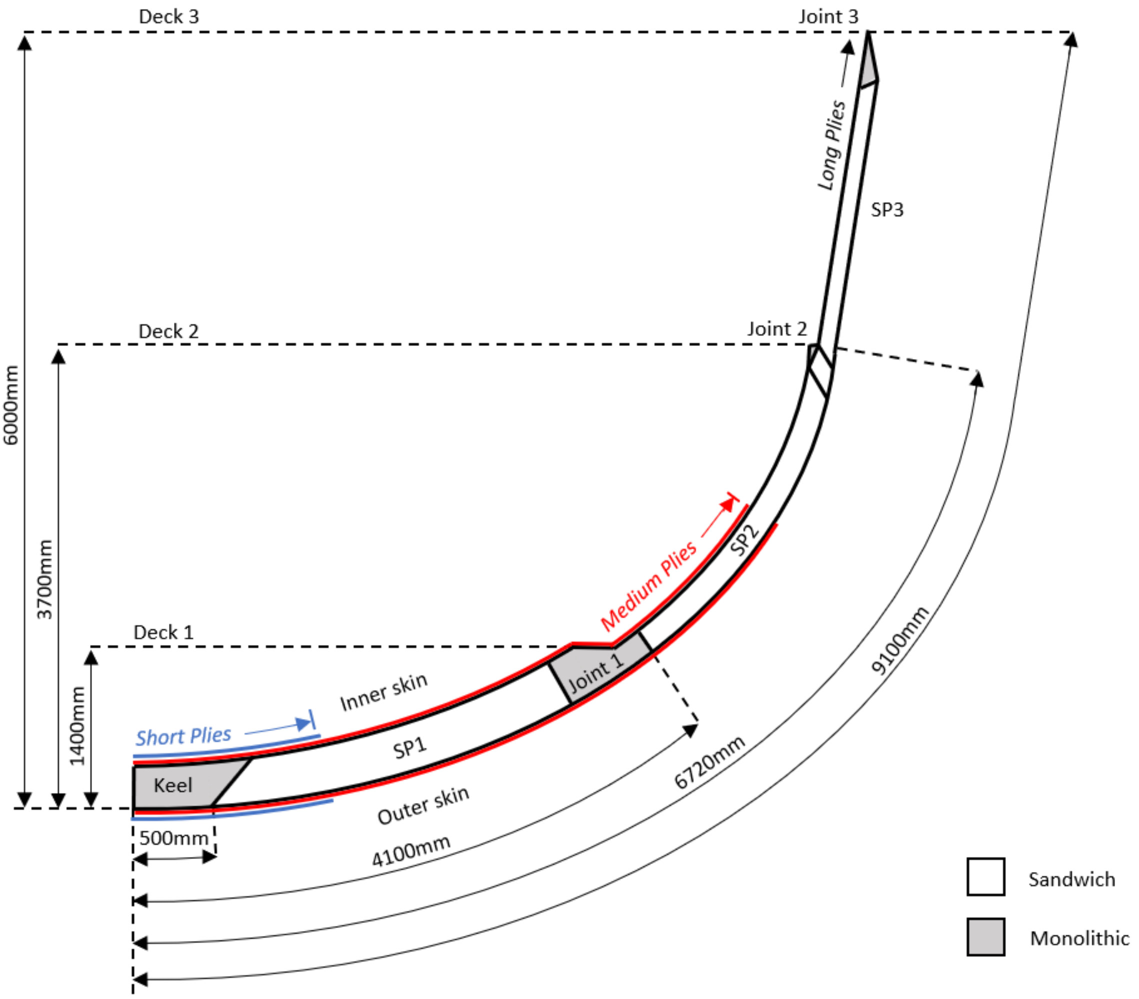


Figure 29: Revised manufacturing design schematic

Table 22: Revised manufacturing design dimensions.

Section	Reinforcement layup						Total section thickness (mm)	Skin thickness (mm)	Core thickness (mm)	Core type	Core sheet thickness (mm)	Ply drops in skin laminates*		Structural transitions*		
	Ply architecture	Stacking sequence	Total QI plies	Total SAER plies	QI plies per skin	SAER plies per skin						Start pos.	End pos.	Name	Start pos.	End pos.
Keel	1200gsm QI (25/25/50)	[SAER], [0/-45/90/+45]9, [SAER], [0/-45/90/+45]9, [SAER], [0/-45/90/+45]11, [SAER], [0/-45/90/+45]11, [SAER],[[0/-45/90/+45]10, [SAER]]22, [0/-45/90/+45], [0/-45/90/+45]9, [SAER], [0/-45/90/+45]9, [SAER], [0/-45/90/+45]11, [SAER], [0/-45/90/+45]11, [SAER]	301	31	-	-	275.4	-	-	-	-	932	2292	Keel/ SP1	500	852
SP1	1200gsm QI (25/25/50)	[SAER], [0/-45/90/+45]12, [SAER], [0/-45/90/+45]13, [SAER], [CORE], [SAER], [CORE], [SAER], [CORE], [SAER], [CORE], [SAER], [0/-45/90/+45]13, [SAER], [0/-45/90/+45]12, [SAER]	50	9	25	3	249.6	23.3	203	GR 200	50	4406	5366	Joint 1	3726	4226
SP2	1200gsm QI (25/25/50)	[SAER], [0/-45/90/+45]6, [SAER], [0/-45/90/+45]7, [SAER], [CORE], [SAER], [CORE], [SAER], [0/-45/90/+45]7, [SAER], [0/-45/90/+45]6, [SAER]	26	7	13	3	128.1	13.6	101	GR 135	50	-	-	Joint 2	6520	6720
SP3	1200gsm QI (25/25/50)	[SAER], [0/-45/90/+45]6, [SAER], [0/-45/90/+45]7, [SAER], [CORE], [SAER], [0/-45/90/+45]7, [SAER], [0/-45/90/+45]6, [SAER]	26	7	13	3	87.1	13.6	60	GR 135	60	-	-	Joint 3	8690	9100

**All positions are given as distances up tool surface from edge of keel at bottom of demonstrator.*

3.9 Conclusions

This chapter presents the reader with an introduction to the RAMSSES project and ship hull shell case study, which will form the basis of the manufacturing research in this thesis. Vacuum bag resin infusion was identified as the most suitable manufacturing process for this structure. A range of suitable constituent materials have been selected for the demonstrator and their relevant process characteristics investigated. The initial structural design was refined to better accommodate the chosen manufacturing process and materials. Modifications to the design include joint support structural details and suitable stacking sequences for glass reinforcement and foam core sheets. These modifications were made in a conservative manner, with the aim to improve manufacturability without compromising structural integrity. This has resulted in a design that is slightly thicker, heavier, and more expensive than the initial design. However, this design is more robust and easier to manufacture. Further optimisation of these features is left for future work.

This work was conducted as industrial led research project within a commercial setting, so time and budget limitations led to a need to rapidly develop feasible solutions. A methodology is presented that describes how the initial details of this manufacturing case study were developed in a rapid and informed manner, using expert opinion and prior experience over detailed experimental and theoretical analysis where possible.

As part of this methodology, extensive, complex problems are divided into smaller, discrete challenges to facilitate a rapid development process. Research questions are identified and solved using a combination of expert knowledge, prior experience, and experimentation. Evaluation matrices are then used to convert these different types of information into quantitative data that can be used to make fair and informed decisions. This approach proved effective at solving complex issues in a cost-effective manner by exploiting industry experience and prior lessons learned. Experimentation was conducted where required to support expert knowledge and provide specific technical information relating to the chosen materials and manufacturing process. This combination of knowledge capture and experimentation was used to generate an initial proposal for the manufacture of a fully composite hull shell. Table 23 outlines the key research questions that were identified and answered within this chapter. The answers to these questions not only help to select suitable materials and refine the design and manufacture of the hull shell, but also to identify the most critical areas of research for the following chapters of this thesis. These research questions may also be beneficial to other similar manufacturing research projects that require a rapid process development approach.

Table 24 presents a summary of the quantitative requirements that were generated throughout this chapter. These requirements are used together with the answers to the research questions featured in this chapter to guide the further development of the manufacturing procedure in the subsequent chapters of this thesis. The final demonstrator manufacturing procedure will also be measured against these requirements to determine the level of success of this project and identify areas for further improvement if necessary. As this is a research project, the applicability of these requirements shall also be reviewed after the demonstrator has been manufactured.

Table 23: List of research questions

1	What is the most suitable composite manufacturing process for a 75m long hull shell?
2	What are the key stages of a resin infusion process for a 75m long hull shell?
3	Which stages of the resin infusion process require the most development?
4	What is the most suitable reinforcement ply construction for the selected case study?
5	Can the selected constituent materials be combined to form a simple laminate of adequate quality?
6	By what amount does the selected glass reinforcement material reduce in thickness due to vacuum compaction?
7	What are the most important resin processing characteristics for the hull shell infusion?
8	What is the most suitable foam core material for the sandwich regions of the hull shell structure?
9	What is the most suitable flow media material for the production of the hull shell?
10	What are the most suitable types of structural transitions for the demonstrator?
11	How many flow media plies should feature in the laminates of the selected case study?
12	What is a suitable ply drop spacing for the structural laminates in the selected case study
13	What is a suitable ply layup pattern for the structural laminates in the selected case study?
14	What is a suitable foam sheet layup pattern for the sandwich regions in the selected case study?
15	What is a suitable gap between foam panels within sandwich regions in the selected case study?

Table 24: Process requirements summary

Requirement	Description	Value
Total man-hours for demonstrator manufacture	Total work required to complete the demonstrator manufacturing procedure from tool preparation to part finishing.	672 man-hours
Maximum infusion duration	Maximum total duration for resin infusion process (excluding laying, vacuum bagging, and cure).	8 hours
Laminate fibre weight fraction	Applied to all structural laminates within the demonstrator.	65% - 72%
Surface accuracy	Geometry of inner and outer surfaces of the demonstrator must not vary from the design schematic by an amount greater than the stated value.	+/-5mm
Longitudinal ply positioning tolerance	Acceptable maximum variation in ply position from design schematic in the longitudinal direction (keel to gunwale)	+/-30mm
Lateral ply positioning tolerance	Acceptable maximum variation in ply position from design schematic in the lateral direction (bow to stern)	+/-10mm
Acceptable defects	A list of defined acceptable defects and their size, frequency, and location within the demonstrator.	See Table 2.
Process robustness	Manufacturing process must be able to operate within prescribed range of ambient conditions.	Temp: 15°C to 35°C, RH: 30% (at 35°C) to 85%

4 INFUSION OF LARGE COMPOSITE MARINE STRUCTURES

4.1 Introduction

Resin infusion was identified in chapter 3 as being the most challenging aspect of the 6m high composite hull shell manufacturing process. This chapter describes the extensive research that was conducted to develop a suitable and robust one-shot infusion strategy for the hull shell demonstrator. This work was conducted in industry as part of a multi-national research project (RAMSSES) and addresses the technical and practical challenges associated with an infusion at this scale.

As highlighted in chapter 1, there is very little evidence of resin infusion processes being applied at the scale required to manufacture large composite hulls (50m+) like the RAMSSES case study (75m). 40m is currently the maximum size of composite hull that is produced by a range of world leading yacht manufacturers. SNSZ Shipyard have previously manufactured an 8.5m high, 6m long, 10m wide demonstrator of a 62m minesweeper hull using resin infusion, however few details are publicly available on this case study (Composites World, 2014). Wind turbine blades are also manufactured using resin infusion, and whilst their lengths are similar to the RAMSSES hull, laminate thicknesses and sectional heights are much smaller than the selected case study (20-100mm vs 300mm). The greater structural height and sectional thickness of the RAMSSES hull shell compared to current yacht/wind turbine designs, in addition to the thick monolithic regions and the presence of complex structural transitions dramatically increases the complexity of the infusion process. The lack of directly applicable existing manufacturing procedures means that extensive research is required to design an effective infusion process for this application.

4.2 Rapid Infusion Development Approach and Risk

The work in this chapter is focused toward the manufacture of a representative hull shell demonstrator, the quality of which being a key indicator of the success of the developed infusion scheme. As outlined in Sections 3.5 and 3.6, the presence of numerous process variables within the vacuum assisted resin infusion procedure increases manufacturing complexity, resulting in a potentially greater risk of defects and process failure. The unique challenges of this novel case study further exacerbate the effects of parameter variations, and therefore increase this risk.

The high-risk nature of this novel manufacturing process results in a need to compromise the extent of research conducted. It is only possible to manufacture one demonstrator in this project due to the large quantities of materials required and budget/resource constraints. A working demonstrator must be produced to facilitate planned structural testing by project partners, and thereby achieve all the deliverables of the RAMSSES project. However, as outlined in Chapter 3, this research project also has a predefined budget and timeframe within which the work must be conducted. Modifications to the rapid development approach are therefore required in order to consider the risks associated with this novel case study. The IPO model presented in Section 3.6 does not consider risk or have the resolution required to support detailed infusion process development. Whilst this work demonstrated how expert opinion and prior experience can provide useful information to support rapid decision making during the initial stages of the project (i.e., material and process selection), these sources of information alone are insufficient for supporting detailed refinements to the manufacturing process. A more detailed analytical approach is therefore required that is directly relevant to, and representative of the demonstrator manufacture in a factory/shipyard environment. Unrepresentative analysis will lead to a greater level of uncertainty in the demonstrator manufacture and thus an increased risk of processing issues and/or failure. The identification of a suitable process development approach is therefore critical for project success.

A spiral development model is used in this chapter to guide the development of an infusion strategy and manage project risk (Boehm, 2000). This rapid application development model is typically used in software engineering; however, it was selected for this case study because it aligns well with the industrial setting and constraints of this project. The author has slightly modified the spiral model presented by Boehm so that it is more applicable to this manufacturing case study. Figure 30 shows the spiral development model used in this project. The process starts with the project requirements at the centre (these are outlined in Section 3.9), moving through each stage of the iterative process and following the spiral outwards to the outer ring, which represents the demonstrator prototype production, evaluation and 75m hull shell infusion plan.

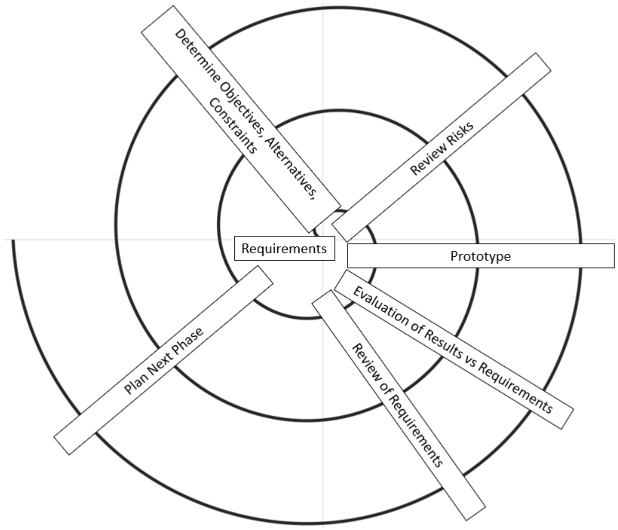


Figure 30: Spiral development model applied to this project (based upon spiral model presented in (Boehm, 2000))

This model features a cyclic process of generating concepts, reviewing risks, developing prototypes, and evaluating solutions against project requirements. In this way, high-value knowledge is incrementally captured through tests by focusing on the most challenging aspects of the project. A solution is progressively developed by continually building on this incremental knowledge with each cycle. There is an inherent level of flexibility built into this approach, allowing the engineer to design and modify test designs and parameters based upon the results of previous tests. This is especially useful for novel research projects where results can be unpredictable, leading to difficulties constructing a detailed test plan prior to initial testing.

This model also addresses project risk, as the evaluation of results against project requirements and analysis of risk is built into every cycle. This risk-driven approach allows for a reduction in development costs and time by eliminating unfeasible options early in the development cycle. For the work presented in this chapter the majority of the risks are reviewed at the start of the spiral development cycle (Section 4.2.1). Any subsequent risks are considered within the individual concept generations and evaluations of results. This iterative approach offers the potential for greatly reducing the duration of the initial development phase and the risks of reworking a solution that does not meet requirements. This model is therefore well suited to rapid developments within an industry setting.

Only three cycles are presented in Figure 30, however in this project a prototype cycle is conducted for each stage of the research. To identify these stages of the research, the complex infusion challenge was divided into fundamental research challenges following the methodology outlined in Section 3.3.

> **Question:** What are the fundamental stages of research that are required to develop an infusion strategy for the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with experts.

The following research stages were identified, each representing one cycle in the spiral model:

- **2D In-plane vertical infusion of thin laminates up to 6m in height**
  This section of work focuses on the specific challenge of a 6m vertical infusion in its simplest form. The goal of this work is to identify the limits of the vacuum assisted vertical infusion process with the selected materials, and thereby devise a suitable infusion strategy for thin, vertical laminates. A series of tests are conducted to understand the effect of hydrostatic pressures acting on the infusion process. It is believed that the hydrostatic pressure will impact the resin infusion speed and pressure gradient, the latter of which may cause a variation in cured laminate thickness with height.

- **2D Through-thickness infusion of thick sandwich sections**

  The goal of this work is to understand the behaviour and limits of the infusion process when applied to horizontal sandwich sections of up to 280mm thickness (based on case study dimensions). This work focuses on the 2D flow of resin through the sandwich thickness, which is primarily influenced by flow channels in the foam core and placement of resin inlets and vacuum outlets. The key challenge here concerns the full wet-out of thick sections, as these preforms can result in complex 3D flow front progression and increased risk of dry spots/defects. Process robustness is a critical factor as conventional means of non-destructive testing (NDT) and defect inspection are not applicable to such large, thick infused composite structures.

- **3D Vertical infusion of thick sandwich sections**

  This work combines the 2D infusion strategies for 2D in-plane and through-thickness infusions. The combined 3D infusion strategy is tested on a representative section.

- **3D Horizontal infusion of thick monolithic sections**

  This work focuses on the development of a suitable infusion strategy for the monolithic keel at the base of the demonstrator. The keel is approximately 275mm in thickness and 500mm long. It is a critical part of the hull structure and must therefore be manufactured to a good quality. Two infusion trials are conducted to understand the limitations of very thick in-plane and through-thickness infusions using the selected materials.

- **Preventing voidage in large infusions**

  Issues concerning voidage within other large, infused structures have been observed at Airborne UK. Initial tests and previous experience have concluded that these voids feature more commonly in larger infusions. It is believed that these voids originate from a combination of processing issues and material selection. An investigation is conducted in this project as a precautionary step to understand the cause of this voidage and to avoid any costly issues later in the development process.

- **Development of an infusion procedure**

  The knowledge gained from the previous infusion trials is combined to develop a suitable infusion procedure for the demonstrator, which is tested on a 6m representative infusion trial. This trial will be conducted as either a physical experiment or as a digital simulation (see next section). The results of this final trial are used to make further refinements to the infusion procedure, which are implemented in the demonstrator manufacture procedure in the following chapter.

- **Demonstrator manufacture**

  Lessons learned from the final infusion trial are implemented into the demonstrator production. The manufacturing process and infused part are evaluated against project requirements. The results are used to generate an infusion plan for the 75m hull shell.

Figure 31 presents the stages of the infusion process development in the form of an IPO model, with each process development step representing one cycle in the spiral development model. This is an expanded version of the "infusion process development" step shown in the IPO model for the entire development process (Figure 19) and is presented here to show how this work fits within the overall methodology of the manufacturing study. The arrows represent the inputs and outputs of each stage and indicate the incremental generation and flow of knowledge throughout the process. The inputs for each stage are the relevant project requirements from Table 24 and the infusion schemes generated in the previous stages. The output of each stage is the proposed infusion scheme for that stage and its evaluation against relevant project requirements in Table 24. Some development steps, such as the "2D In-plane vertical infusion of thin laminates" feature multiple cycles within them in order to investigate multiple effects, but this is not shown in the diagram to preserve clarity.

Research questions are identified for each process development step based upon the fixed and variable inputs. Due to the novel nature of this study and the potential unpredictability of results, some additional research questions are identified during the work based upon experimental findings. Research questions are answered using the methodology presented in Section 3.3.

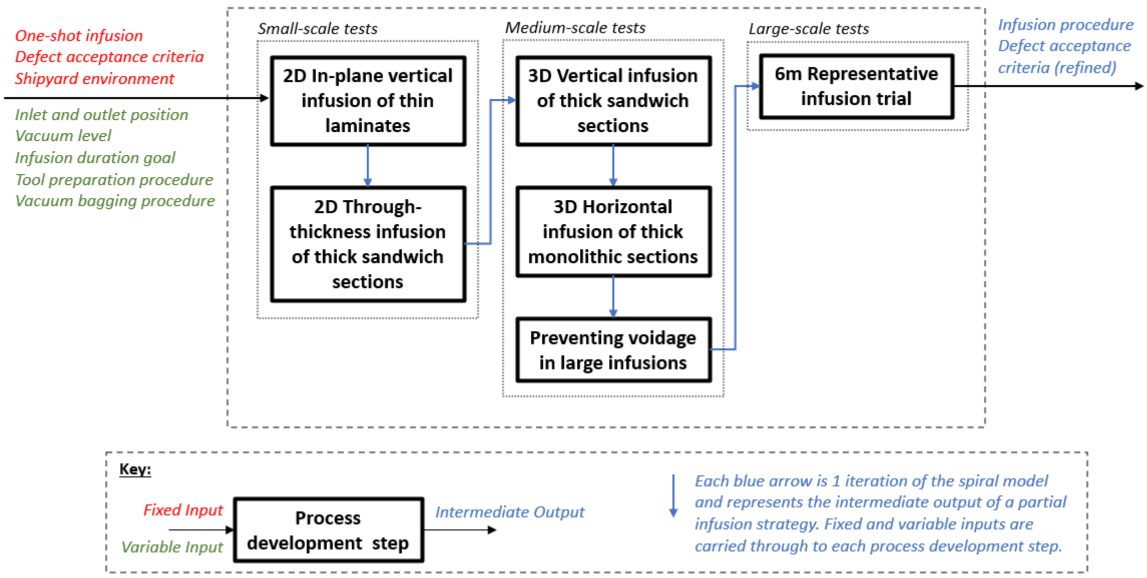


Figure 31: IPO Model specific to infusion process development

4.2.1 Selection of suitable analytical method

The tests outlined in Figure 31 can be conducted using either an experimental or simulation approach. A suitable analytical method must be selected.

> **Question:** What is the most suitable analytical approach for developing an infusion process for the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with experts with experience in both composites manufacturing and resin infusion simulation.

The following evaluation criteria were identified:

- **Available resources and expertise at Airborne UK (at time of conducting research):** Aligning the research approach with available resources and expertise will enable the use of prior knowledge and experience to support decision making, leading to a more rapid development approach.
- **Cost:** Estimated relative total cost of approach based upon total resources and man-hours required to execute research. Large scale physical experiments will likely incur high materials and labour costs, whilst simulations may incur higher initial costs associated with software acquisition and training.
- **Duration:** Estimated relative total duration of the research. A shorter duration is preferred due to the need for a rapid development approach.
- **Knowledge gained:** A relative comparison of how useful the results are from each approach and how they can be used to develop an infusion strategy.
- **Project risk:** A relative measure of the level of risk associated with each option. This is somewhat dependant on prior experience and expertise. It is very important that the tests, and therefore the results, are representative of the demonstrator manufacture.

Three research approaches are considered: practical experiment, digital simulation, and a combination of both. A decision matrix was used to compare these options.

Table 25 indicates that an experimental approach is slightly more suitable than the other options for developing an infusion strategy for this case study. It is important to note that this conclusion is made based upon the specific novel details and challenges of the hull structure and the unique restraints and industrial setting of this project. This is not a generalised statement of which approach is better in industry, as each unique project will have different challenges and constraints.

Table 25: Comparison of different analytical approaches for the development of an infusion strategy. Valid only for the selected case study, conducted at Airborne UK (information true at time of creating matrix, June 2017)

Evaluation criteria *(weighting)*	**Experiment** A series of physical infusion trials are conducted to understand the infusion process within representative sections, supported by industry knowledge and experience.	**Simulation** A series of flow simulations are conducted to understand the infusion process. Physical experiments are limited to small lab-scale tests to determine material properties such as reinforcement permeabilities.	**Experiment and Simulation** A combined approach in which a limited number of physical representative experiments are used to support and validate numerous simulations.
Available resources and expertise *(1)*	All equipment and resources required for infusion trials is readily available. Manufacturing experts available to provide insight and prior experience to support rapid decision making and process development.	Limited experience in infusion flow simulation at Airborne UK when this decision was made. Flow simulation software would need to be purchased. Some expertise available from universities and software developers.	Limited experience and resources available for flow simulation. Company capabilities should be expanded to fully exploit this option.
Cost *(3)*	Large scale infusion trials can be costly due to material and labour costs. Infusions also require significant quantities of consumable materials (vac bag, infusion pipework, etc…). Cost of experiments increases with number trials and size of part.	Potentially high initial cost for software, but low cost for executing individual simulations. Cost per simulation dependant on man-hours to complete each simulation and is generally independent of part size.	Potential for reduced costs compared to experimental approach, however the initial costs of setting up simulation capability is predicted to offset cost-savings linked to reduced number of experiments for this short, novel study.
Duration *(3)*	Conducting experiments and analysing results may take time, especially for larger parts. A typical infusion trial could take 2-5 days to conduct (including design, setup, analysis of results and clean up). Existing infrastructure means infusion trials can commence immediately. Expert knowledge and prior experience can support the investigation and enable faster decision making.	Individual simulations could be completed faster than experimental trials (1-2 days: including model setup, simulation, and analysis of results), allowing more infusion configurations to be investigated. However, initial setup time is predicted to be quite long: A suitable software package must be identified and learned, and simulation input parameters (material properties) must be quantified via experiment.	Potential for a rapid development approach (faster than experimental and simulation options), however short project duration and lack of resources/simulation capability means this combined approach may lead to a greater overall project duration for this short, novel research project.
Knowledge gained *(3)*	Representative experiments provide data on resin flow and infusion speed, as well as insight into appropriate manufacturing methods, material behaviour and realistic manufacturing tolerances. Produced parts can be inspected for quality/defects, providing a useful link between process parameters and quality.	Simulation can provide data on resin flow and infusion speed. Many more simulations can be conducted compared to physical experiments, allowing for a vast range of different infusion strategies to be studied.	Simulation and experiments complement each other, providing the ability to conduct a wide range of representative and validated simulations in a cost-effective manner, whilst quantifying part quality through physical tests.
Project risk *(3)*	Provided the trials are representative, all manufacturing variables are incorporated into the tests. Additional/unforeseen manufacturing challenges can be identified during these experiments to aid process development, reducing the risk of sudden process issues arising during demonstrator production.	The novelty of this challenge (size, thickness, gravity effects) and the large number of unknown process variables means it is very difficult to create a truly representative analysis using simulation alone. Lab-scale tests to determine material properties may not be representative, leading to differences between simulation and demonstrator production.	Representative trials provide insight into potential manufacturing challenges and allow representative data to be collected for use in simulations. Simulations can "fill in the gaps" between experimental data.
Total Score	**30**	**29**	**29**

Table 25 presents the strengths and weaknesses of each approach. An experimental approach was selected primarily because it was identified as being the lower risk approach, whilst better aligning with existing infrastructure and experience at Airborne UK to support a rapid process development. However, it appears that the two options complement each other, and when applied together could provide a fast, cost-effective approach with reduced project risk. A combination of simulation and experiment would enable a large number of infusion strategies to be modelled fairly rapidly, with a limited number of carefully selected physical experiments providing representative material properties, validation of simulation results and a link between part quality and process characteristics/design. Whilst this combined approach has the potential to be faster and more affordable than the individual approaches, the lack of existing infusion simulation infrastructure and experience available at Airborne UK is predicted to increase overall development time and cost. Ultimately, it was deemed unsuitable to incorporate such a significant expansion of the company's capabilities within this short, novel, and high-risk research project.

The experimental approach was deemed lower risk than a simulation-only approach for this case study due to the complexity of the novel large-scale infusion (i.e., large sectional thickness, vertical infusion and combination of various sandwich and monolithic regions) and the predicted challenges associated with accurately quantifying all process variables required for generating representative simulations. For example, reinforcement permeability greatly impacts the speed and direction of resin flow during the infusion process, so permeability values must be accurately quantified to generate truly representative simulations. This is typically done via experimentation (Pierce, R., Falzon, B., 2017) (Lundstrom, 2000). However, reinforcement permeability is dependent on the laminate architecture, (which can vary across a test sample due to variations in ply manufacture, handling, and layup/draping) and achievable vacuum compaction (which is dependent on vacuum bag integrity, which is difficult to predict for such a large, novel structure). Arbter et al. demonstrate how different people conducting different procedures for measuring in-plane permeability values can lead to a significant scatter in measured permeability results of up to 1 order of magnitude (Arbter, R., et al., 2011). This highlights the importance of conducting experimental tests that are representative of both the final part and procedure. Due to the complexity of the hull shell, multiple representative trials would need to be conducted for each discrete region of the structure (monolithic keel, SP1, SP2, SP3, all joint details) to account for variations in laminate/section architecture, thickness, inclination/position on tool (which may influence how the material is laid up), and general layup procedure. Without these tests, it is difficult to accurately quantify the input process variables required for accurate simulations.

The remainder of this chapter therefore focuses on the development and execution of representative experimental trials, supported by industry knowledge and experience to address the research topics outlined in Section 4.1. This work shall be guided by the process requirements presented in Table 24, Section 3.9.

The following data shall be recorded, where appropriate, for each experiment to support the development of an infusion process that meets the process requirements:

- **Resin flow speed/infusion speed:** A measure of how long the resin takes to infuse through a specific part. This information can be used to estimate the duration of the demonstrator infusion (assuming a scaled-up version of the infusion strategy applied within the experiment), which can indicate the suitability of different infusion strategies. Resin flow speed is recorded via periodic measurements of resin flow front position with time during the infusion process. An 8-hour maximum infusion duration is defined as a process requirement.
- **Resin wet-out (during infusion):** A measure of how much of the preform is wet-out during the infusion process. This gives an immediate indication as to the suitability/success of specific infusion strategies. Overall resin wet-out is determined via visual inspection during and immediately after the infusion process. Identification of dry spots which exceed the acceptable criteria outlined in Table 2 may indicate the need for modifications to the infusion procedure. It is important to highlight the difference between resin wet-out during the infusion and part inspection after cure (discussed below). It is possible for an issue to occur after the infusion that results in dry spots or other defects. By taking measurements/visual inspections at various stages throughout the procedure, one can better identify the cause of process issues.
- **Fibre weight fraction:** Fibre weight fraction of samples are calculated based upon measurements of cured laminate thickness and constituent material properties. This is a fast and cost-efficient approximation that can be made with non-specialist equipment available within a typical factory. This approach assumes 0% voidage fraction, which is considered to be an acceptable assumption provided that the laminate passes the visual inspection of part quality (described below). Total section thicknesses are measured after cure at 4 locations, which are used to calculate an average cured ply thickness value for each specimen. The fibre weight fraction is compared against the allowable range defined in Table 24. Equations (10) and (11) are used to determine fibre volume and weight fractions respectively (ASTM, 2011) (B. T. Astrom, 1997):

$$\boldsymbol{V_f} = \frac{(A_r N \frac{1}{10})}{(\rho_f h)} \tag{10}$$

$$\boldsymbol{W_f} = \frac{V_f \rho_f}{V_f \rho_f + V_m \rho_m} \tag{11}$$

Where V_f = fibre volume fraction, V_m = matrix volume fraction, W_f = fibre weight fraction, A_r = reinforcement areal weight (1200 g/m^2), N = number of quadaxial plies**, ρ_f = fibre density (2.54* g/cm^3), ρ_r = cured resin density (1.123* g/cm^3)*

**Data supplied by material manufacturers/suppliers.*

***Saerflow plies are not included in fibre weight fraction calculations to generate a conservative estimate (i.e., slightly lower weight fraction than reality).*

- **Visual inspection of part quality:** The part is inspected after cure to identify the presence of any defects (allowable defect criteria outlined in Section 3.2.1). Depending on the specific details of the specimen (thickness, geometry, composition) it may be suitable to cut sections out of the part to visually inspect deep within the specimen. Any defects that do not conform to the allowable defects criteria are highlighted, and attempts are made to identify the cause of these defects such that they do not occur within the demonstrator manufacture.

4.3 2D In-Plane Vertical Infusion of Thin Laminates

The first step in the development of an infusion strategy is to understand the basic limitations of the vertical infusion process. This work primarily addresses the challenge of raising resin up to 6m in height against the force of gravity.

In a typical vacuum assisted resin infusion process the movement of resin through a porous preform is driven by the pressure differential across the system. This behaviour can be described by Darcy's Law (Popham, 2019), Equation (12):

$$Q = \frac{kA\Delta P}{\mu L} \tag{12}$$

Where Q = volumetric resin flow rate, k = preform permeability, A = preform cross sectional area, ΔP = pressure differential, μ = resin dynamic viscosity, L = distance from inlet to flow front.

Volumetric resin flow rate dictates the overall speed of the infusion. This must be controlled so that the infusion duration is shorter than the cure time of the resin. However, an excessively high flow rate may not provide the resin with enough time to fully penetrate the fibre tows, resulting in dry regions within the part. The resin flow rate through the demonstrator preform is predicted to be insufficient for achieving the desired 8-hour maximum infusion duration (see Table 24) without development of an effective infusion strategy. The goal of this work is therefore to increase the resin flow rate by modifying the other parameters. Experimental trials are an effective method for determining suitable quantities for the various parameters, and hence a flow rate that meets the requirements.

Reinforcement permeabilities and resin viscosity are material properties that are mostly determined at the material selection stage. However, these variables are not fixed. Overall laminate permeabilities can be modified by adding flow media and the resin viscosity can vary with temperature and degree of cure. Implementing flow media within laminates can lead to a faster infusion process, as demonstrated in Chapter 3. The flow media (Saerflow) previously selected in Chapter 3 shall be incorporated within all laminate infusions featured in this chapter.

The preform cross sectional area and length cannot be significantly modified as they are dependent on the structural design requirements. Darcy's Law dictates that the greater the distance between the flow front and resin inlet, the lower the volumetric resin flow rate. Whilst the preform length may be fixed, effective placement of resin inlets and vacuum outlets can reduce the distance that the resin must travel from each inlet.

The pressure differential is created by applying vacuum suction at one (or several) points in the system. For a horizontal infusion at ground level there are two primary pressures acting on the system: the pressures at the resin reservoir (inlet) and the vacuum pump (outlet). It is assumed that the resin reservoir is open to atmosphere, and therefore the pressure at this point is equal to atmospheric pressure (1 bar). The pressure at the vacuum pump can be set at any value between 0 and 1 bar. Therefore, the theoretical maximum pressure differential across a typical vacuum assisted resin infusion process is 1 bar.

When an infusion is raised vertically from the ground an additional hydrostatic pressure acts on the system. This pressure acts downwards and is dependent on the height of the resin flow front from the reservoir. Equation (13) shows how this pressure affects the overall pressure differential across the system.

$$\Delta \boldsymbol{P} = \boldsymbol{P}_{atm} + \boldsymbol{P}_{vac} + \boldsymbol{P}_{hyd} \quad (13)$$

$$\boldsymbol{P}_{hyd} = \boldsymbol{\rho}.\boldsymbol{g}.\boldsymbol{h} \quad (14)$$

Where P_{atm} = Atmospheric pressure at reservoir, P_{vac} = Pressure at vacuum pump, P_{hyd} = Hydrostatic pressure, ρ = liquid resin density, g = acceleration due to gravity, h = height of resin flow front from reservoir.

The following sign convention for equation (13) is applied in this thesis: Any pressures acting in the direction of the resin flow are positive, whilst pressures that act in the opposite direction are negative. Figure 32 depicts the pressures acting on a vertical infusion. It is assumed that the resin is infused upwards with the resin reservoir below the part. This is explained in further detail in a later section. The sign convention is applied to express the pressure differential for this specific infusion in Equation (15).

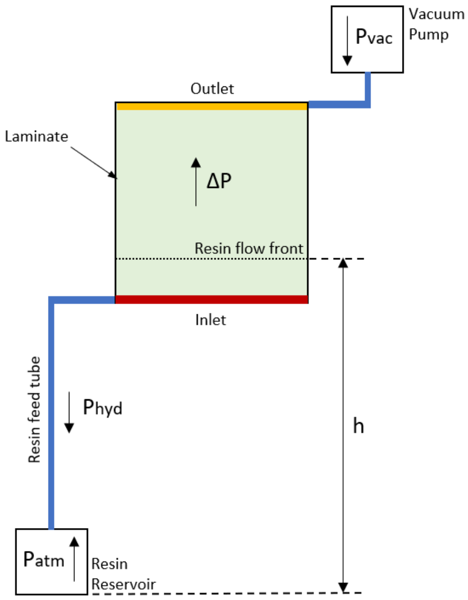


Figure 32: Pressures acting on a vertical infusion

$$\Delta P = P_{atm} - P_{vac} - P_{hyd} \qquad (15)$$

In this scenario the hydrostatic pressure acts against the resin flow, resulting in a lower pressure differential across the system. Assuming P_{vac} = 0, there is a theoretical maximum height at which the hydrostatic pressure is equal in magnitude to the atmospheric pressure. This creates a zero-pressure differential and stops the resin flowing any further. The first stage of this work is to identify this limit for the selected materials.

4.3.1 Resin flow in a vertical tube

This initial investigation is conducted to determine the maximum height to which the resin can be lifted under vacuum. The results of this test essentially define a limit on the height to which resin can be vertically infused.

Question: What is the maximum height to which the resin can be lifted under vacuum?

Data acquisition method: Experiment

In this experiment resin is drawn up a transparent vertical tube, with the bottom end submerged in a container of resin and vacuum applied at the top end. Three experiments were conducted using different resins and equipment to gain a better understanding of the physical limits of vertical infusions. In each experiment, unmixed resin was slowly brought up the tube by periodically lowering the pressure inside the tube. The resin was left for 3 minutes at each incremental pressure level to settle before the height was measured.

Theoretically, the resin height achievable in this test is the point at which all forces acting on the system are in equilibrium. Equation (14) can be rearranged to calculate the height at which resin can be lifted for a given vacuum level (Equation (16)).

$$H = \frac{\Delta P}{\rho . g} \qquad (16)$$

In this initial experiment pressure losses due to frictional forces in the pipe are assumed to be low and are not accounted for. Therefore, for this initial study ΔP is assumed to be equal in magnitude to the reading on the vacuum gauge.

Table 26: Resin flow in vertical tube: Experimental setup.

Experiment	Resin	Density (kg/m^3)	Max tube height (m)	Tube diameter (mm)	Temperature (°C)
1	Albidur 3.2	1010	6	10	19
2	Prime 27	1130	6	10	19
3	Atlac E-Nova MA6215	1050	12	20	15

This experiment was conducted with three different resins of similar density. Table 26 outlines the parameters for these three experiments.

The results of these experiments are presented alongside theoretical predictions (using Equation (16)) in Figure 33. The experimental results match closely to the theoretical predictions and indicate that approximately 9 to 10 metres is the maximum achievable height that resin can be raised using only vacuum suction, depending on the resin used. The data also shows that whilst an infusion at 6m high is possible with Albidur resin, the maximum pressure differential available for the infusion is 0.4bar. This could be problematic as lower pressure differentials typically result in lower laminate fibre volume fractions, and hence laminate properties. Resin infusions are generally conducted with pressure differentials of 0.5 to 1 bar.

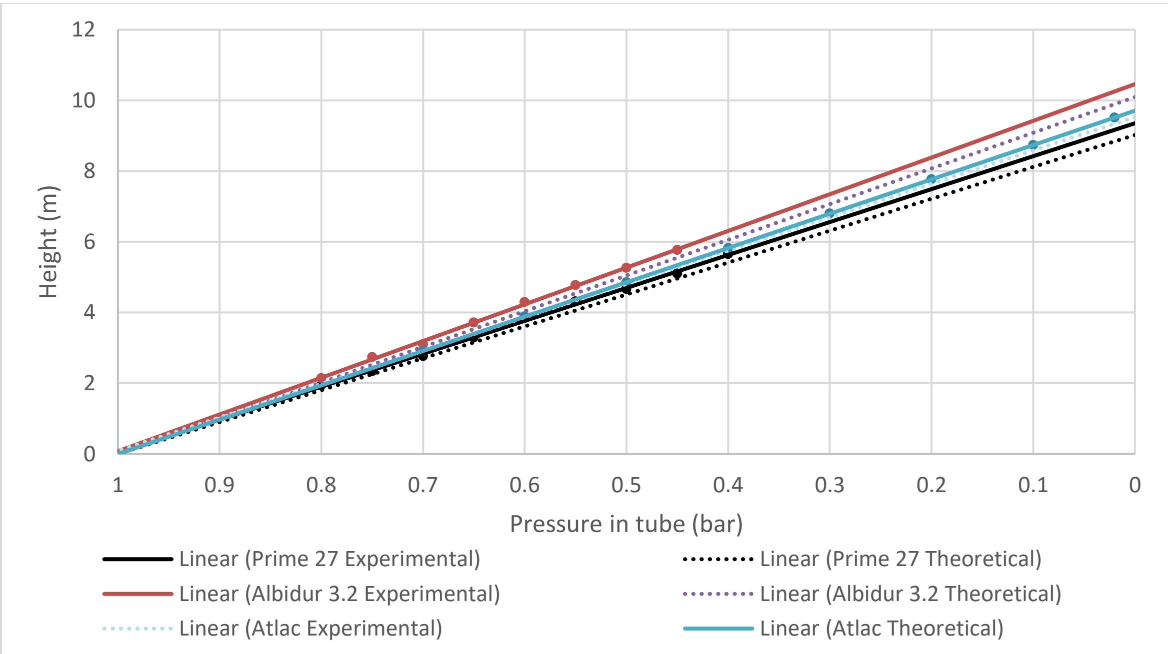


Figure 33: Resin flow in vertical tube experimental and theoretical results

Having identified the height limit for vertical infusions, it is now possible to construct an infusion strategy for thin vertical laminates. This infusion strategy is developed by primarily controlling three parameters in Darcy's Law (Equation (12)): k, L and ΔP. The following three sections of this report investigate ways to control these three parameters.

4.3.2 Inlet and outlet configuration

Equation (12) indicates that the distance resin must travel from the inlet, L is inversely proportional resin flow rate. L can be reduced through suitable placement of resin inlets and vacuum outlets. A suitable inlet and outlet configuration should therefore be identified that reduces infusion distance, and thus infusion duration. This configuration will then be refined further throughout this chapter.

> **Question:** What is the most suitable inlet and outlet configuration for infusing thin laminates of comparable geometry to the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with experts, supported by experiments where required.

It is important to note that the inlet and outlet configuration will also influence other factors of the infusion process, which must be considered when making the selection. The following evaluation criteria were identified based upon the project specification requirements and expert opinion.

- **Robustness:** Sensitivity to variations in process parameters and likelihood of these variations causing lock-offs/defects.
- **Ease of setup:** Simple inlet/outlet configurations are preferred. The greater the configuration complexity and inlet number, the greater the setup time, cost and likelihood of errors being made.
- **Total infusion duration:** The infusion duration is heavily dependent on infusion distance, L. However, additional factors such as the number and size of inlets also influence the resin flow rate. The overall infusion duration will affect production rates and costs, as well as the required resin gel time. Evaluations of infusion duration are based upon previous experience and focus on highlighting the extremes rather than the finer details of these as yet unrefined configurations.
- **Compatibility with 75m hull infusion:** It is important to consider how each configuration would be applied to both the demonstrator and 75m hull infusion. Configurations that are not compatible should be neglected at this stage.

Figure 34 depicts some examples of infusion configurations for the 2D demonstrator geometry (i.e. a thin laminate) that can be used to reduce L compared to the baseline setup (configuration A). Configuration B divides the infusion into smaller, repeatable units to significantly reduce L. In this scenario the inlets are progressively opened after the resin flow front has passed their position. Configuration C is similar to B, although this infusion is instead conducted from top to bottom, and therefore aligned with the hydrostatic pressure rather than against it. Configurations D and E take advantage of the preform geometry to create an infusion path across the width and thickness, respectively. These configurations achieve a shorter resin paths without the need for additional inlets. Configurations F and G feature radial infusions, which can be beneficial in some cases, depending on part geometry. Configuration H features an addition vertical inlet component to reduce the distance the resin must travel. This configuration is based upon existing composite boatbuilding experience.

It should be noted that a minimum distance between inlets of 1m was initially set made based upon prior experience with other commercial infusion processes. This value was determined to be a good compromise between infusion speed, quantity of consumable products and layup/bagging time. No limit was set for the maximum distance between inlets, as this would be determined by the resin flow speed and gelation time. Suitable inlet spacing will be investigated further within this chapter.

Figure 35 shows how configurations A to H could be applied to a 75m ship hull infusion. It is important to note that the demonstrator infusion must be as representative of the 75m hull shell infusion as possible. The chosen configuration must therefore be compatible with a 75m hull shell infusion provided the scheme features an appropriate level of risk when applied to the demonstrator infusion. As a result, configuration D has been modified to include multiple inlets as it is not practically possible to infuse resin over a 75m distance with a single inlet using the selected materials. Table 27 evaluates the infusion configurations from both Figure 34 and Figure 35 against the evaluation criteria to enable selection of the most suitable option.

The evaluation in Table 27 indicates that configurations A, E, F and G cannot be practically applied to a 75m hull shell infusion without considerable risk, and so these options are neglected. Configurations D and H appear to be good choices for the demonstrator infusion; however, they are not fully compatible with the 75m hull shell. Configuration D’s excessive total infusion duration is its greatest limitation, and realistically this would not be a feasible option for a commercial shipyard. Configuration H appears to be a simple and relatively robust option for infusing a thin 75m hull shell. However, the non-uniform flow front combined with potential variations in preform permeability due to layup tolerances increases the risk of dry areas (i.e., lock-offs) forming in the central core of thick sandwich panels. This is deemed an unacceptable risk and so this configuration is also neglected. Configurations B and C both appear to be good choices. Whilst the downwards infusion of configuration C is expected to be slightly faster, there is a much greater risk of dry areas forming at the outlet when applied to a symmetric hull. Furthermore, in a downwards infusion the resin flows in the same direction that the hydrostatic pressure acts, increasing the risk of resin pooling and ballooning the vacuum bag at the bottom of the part. Configuration B is therefore selected as it the most compatible with the 75m hull shell infusion and is awarded the highest score in Table 27. This configuration can be applied to the demonstrator infusion with an acceptable level of risk and can be easily scaled up to the 75m hull shell with minimal changes.

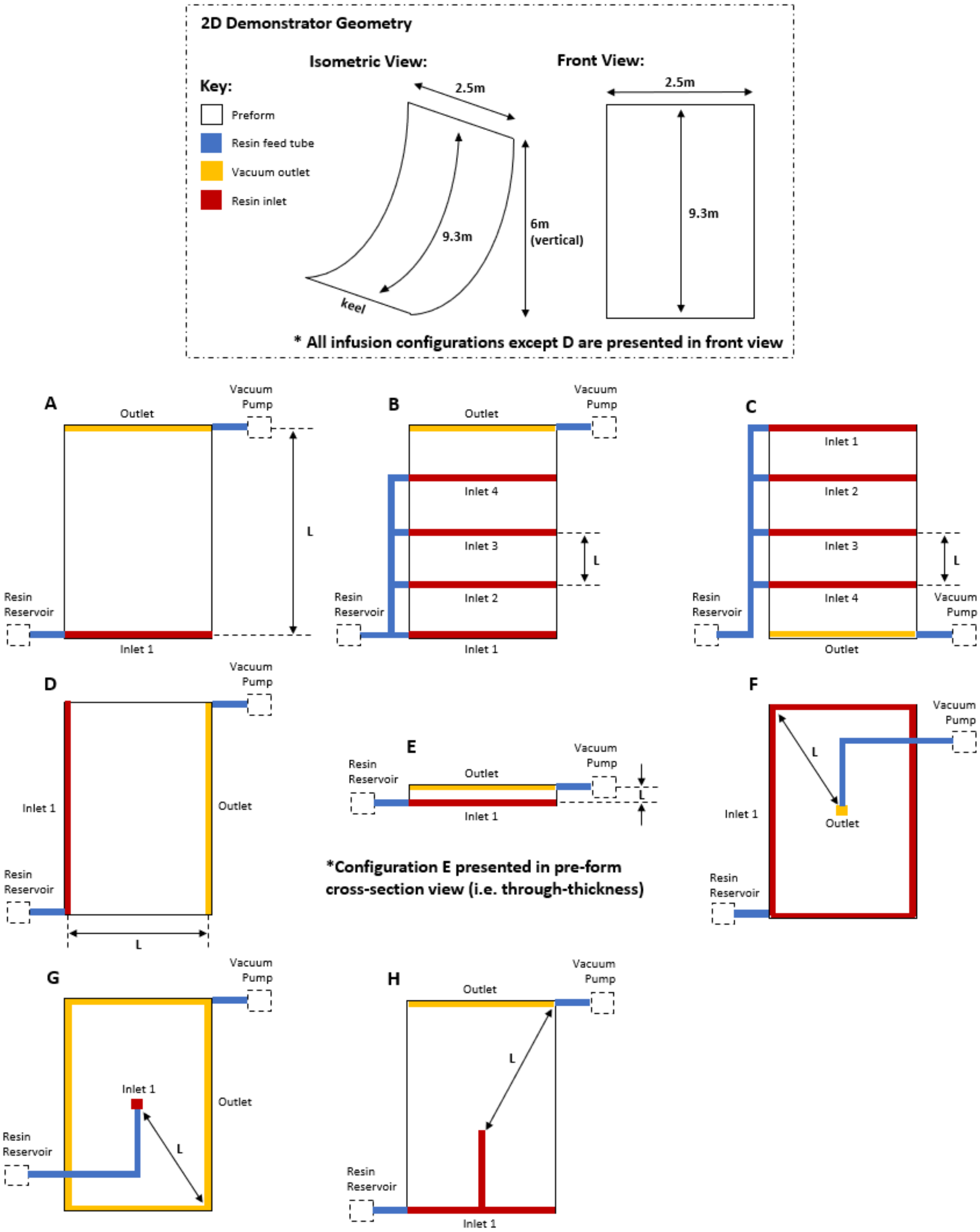


Figure 34: Alternative 2D demonstrator infusion configurations to improve resin flow rate

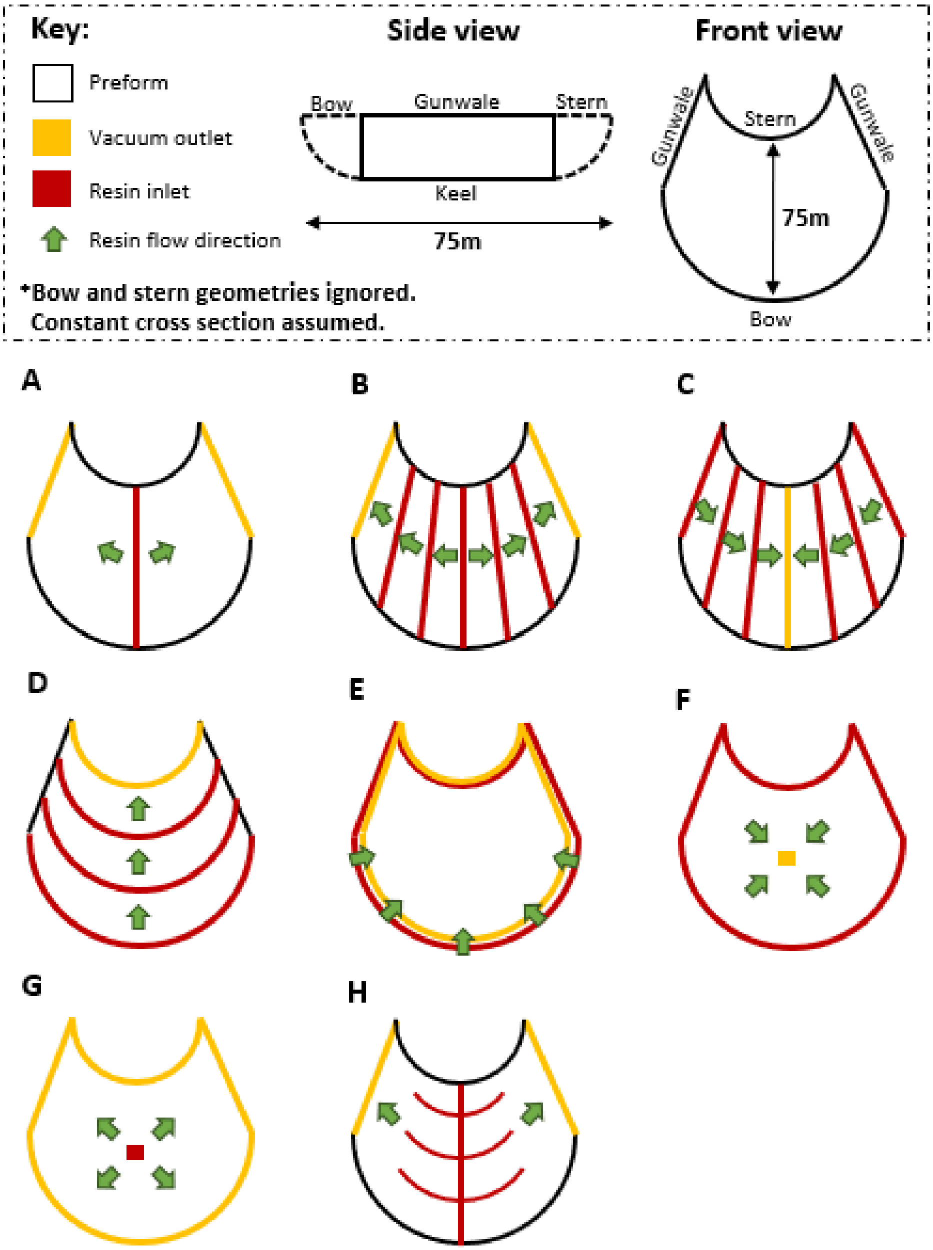


Figure 35: Infusion configurations for 2D 75m hull shell (ignoring bow and stern geometries and assuming a constant cross section over 75m).
Configurations A to H correspond to those featured in Figure 34 but are slightly modified where appropriate to improve compatibility with a 75m hull shell infusion.

Table 27: Evaluation of infusion configurations for demonstrator (Figure 34) and 75m hull (Figure 35). Supporting experiments provided in the appendix [A.3] and [A.4].

Criteria *(weighting)*	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Robustness *(3)* (Figure 34)	Simple infusion with the minimum number of inlets and outlets. A single resin flow front moves through the preform, reducing risk of lock-offs.	A more complex infusion with multiple inlets. Single resin flow front reduces risk of lock-offs. Success somewhat dependent on operator (opening inlets at the correct time).	Same robustness rating as configuration B.	Hydrostatic pressure varies with height; therefore, the keel will infuse faster than the gunwale, resulting in an irregular infusion. [A.3]	The short infusion distance combined with a large outlet surface area increases sensitivity to process variations and may result in localised lock-offs if the resin does not move through the thickness uniformly.	The outlet must be positioned precisely where circular resin flow front converges at the centre to avoid lock-offs. This setup is highly sensitive to process variations.	A simple process to execute with a single flow front moving radially outwards. However, gravity effects will result in a non-symmetric infusion which may lead to defects.	Non-uniform single flow front travels from keel to gunwale. Variations in preform permeability due to layup tolerances may lead to lock-offs.
Ease of implementation *(2)* (Figure 34)	Simple to setup with minimal input required once started.	Multiple inlets to setup, but complexity is low. Requires good timing when opening inlets to avoid lock-offs.	Same challenges as configuration B.	Simple to setup with minimal input required once started.	Creating an inlet and outlet on the top and bottom surfaces of the demonstrator is difficult in practice. Any discontinuities in the surface inlet may compromise process robustness.	A potentially large resin inlet and central through-bag outlet connection must be created. Minimal input required once the infusion has started.	A potentially large resin outlet and central through-bag inlet connection must be created. Minimal input required once the infusion has started.	Simple to setup with minimal input required once started.
Total infusion duration *(2)* (Figure 34)	The resin must travel over a large distance between the inlet and outlet. Infusion duration predicted to be very slow and may not finish depending on the height.	Resin travels shorter distances between each inlet, resulting in a faster infusion than configuration A. However, the resin travels over the longest length, so duration is expected to be longer than other configurations.	Slightly faster than configuration B as gravity aids the downwards infusion. [A.4]	Resin path shortened compared to configuration A, therefore infusion duration is expected to be lower.	Infusion duration is expected to be very fast as the resin path is the shortest of all configurations.	Resin inlet over a large surface area combined with reduced resin path length leads to a reduced infusion duration compared to configuration A.	Small central inlet may restrict resin flow rate, leading to a longer infusion. However, the resin path is much shorter than configuration A, and so duration is expected to be shorter.	Resin infusion path shorter than configuration A, therefore duration is expected to be lower.
Compatibility with 75m hull shell infusion *(3)* (Figure 35)	Simple setup, however, excessive infusion path distance of 9.3m will result in resin curing before infusion is complete.	Shortest practical infusion path with regular inlets to maintain resin flow rate throughout infusion.	Similar to configuration B, however for a symmetric hull infusion two flow fronts meet at the central outlet, increasing risk of lock-offs.	Regular inlets to maintain resin flow rate, however 75m total infusion path results in a long process duration.	Impractical to setup, requiring an elaborate and costly tool surface design. High risk process, although this is theoretically the shortest infusion path available, so infusion duration is expected to be very low.	Impractical due to 30m+ infusion path length. Resin will cure before infusion is complete.	Impractical due to 30m+ infusion path length. Resin will cure before infusion is complete.	Effective process for thin laminates, however the non-uniform flow front may cause issues with 200mm thick sandwich panel infusions.
Total Score	20	23	20	22	17	14	17	22

4.3.3 Pressure differential

An improved understanding of the selected infusion strategy is required before selecting an appropriate inlet spacing, L. To do this, several experiments are conducted to identify the limit of this infusion configuration and understand the effects of various parameters such as the pressure differential.

Darcy's Law (Equation (12)) shows how the pressure differential, ΔP across an infusion is directly proportional to the resin flow rate. It was previously described how the height of an infusion can reduce ΔP due to hydrostatic pressures acting on the system. This section explores potential modifications to the infusion scheme to reduce the effects of hydrostatic pressure and maximise ΔP.

4.3.3.1 Effect of vacuum level

Equation (15) shows that varying the applied vacuum level is one way to alter the pressure differential across the system. Generally, a maximum vacuum level of -1 bar is preferred for infusion processes as this results in the maximum pressure differential, and thus fastest infusion and higher fibre volume ratios. However, it is not yet clear what vacuum level would be achievable for the demonstrator (and 75m hull) infusion. Furthermore, high vacuum suction may lead to increased levels of voidage due to volatile substances being extracted from certain resin systems during the infusion process (discussed further in Section 4.7). It is therefore important to understand how the infusion behaves across a range of suitable vacuum levels.

Question: What is a suitable vacuum level range for the infusion process?

Data acquisition method: Experiment, supported by industry experience.

Three vertical infusions were conducted with the selected materials to investigate how the resin flow speed varies with both height and vacuum level. Vertical infusions were chosen over horizontal infusions because they also incorporate gravity effects, and therefore represent the worst-case scenario. All three preforms were 0.25m wide by 3m high and consisted of 1 ply Saertex quadaxial and 1 ply Saerflow. The preforms were contained within an envelope vacuum bag and hung vertically with the bottom of each preform at ground level. A single resin inlet was located at the bottom of each preform, spanning the full 0.25m width. The infusions were conducted at 22°C with Albidur 3.2 resin and vacuum levels of -0.9, -0.7 and -0.5 bar. These vacuum levels were selected to represent the range that could be used in the demonstrator infusion. -0.5bar was identified as the minimum suitable vacuum level based upon industry experience. -0.9 bar was the maximum vacuum level achievable with the available equipment during these initial infusion trials, although a dedicated vacuum pump would later become available to achieve -1 bar for the demonstrator infusion. Figure 36 shows the infusion setup and Figure 37 shows the measured resin height against time for the three infusions.

It should be noted that the author conducted many variations of the thin vertical infusion trial over the course of the manufacturing study and found the resin flow front pattern (black lines in Figure 36) to be mostly consistent over all experiments. The envelope vacuum bag was effective at restraining any undesirable edge effects (i.e., race tracking), and any slight skew in the flow front progression (as shown in Figure 36) was due to variation in inlet handling and layup. For the purposes of this experiment, this effect was found to be minimal. Furthermore, flow front positions were averaged across the laminate width for consistency.

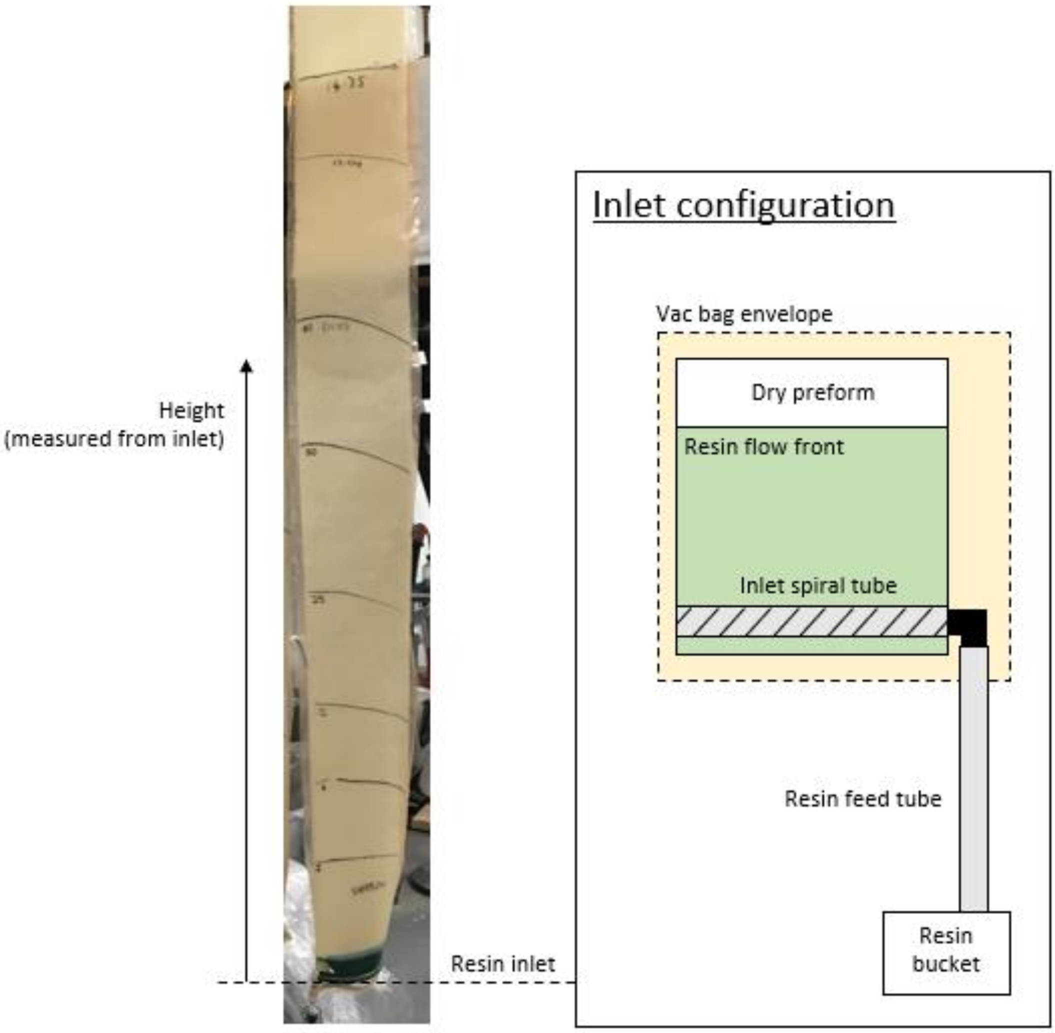


Figure 36: Thin vertical infusion setup

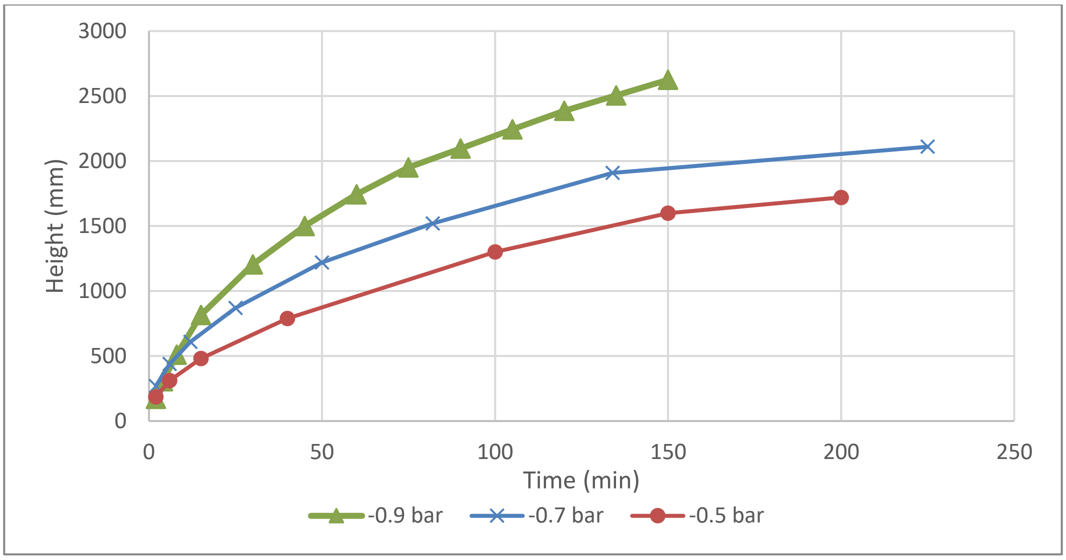


Figure 37: Resin flow front height vs time for thin vertical infusions at different vacuum levels (inlets at height = 0m)

As predicted, the applied vacuum level significantly affects the resin flow rate of thin, vertical infusions, with a vacuum level of -0.9 bar providing the fastest infusion. It is also important to consider the maximum height which this setup can raise the resin. The resin flow rate in all three tests appears to decelerate significantly after 2 to 3 hours with heights of 1.5 to 2.5 metres being achieved. Based upon the data it is predicted that the -0.9 bar infusion could achieve a height of approximately 3 metres before resin gelation at 4 hours. It is therefore apparent that none of these infusions would be able to achieve a 6m vertical height before gelation, and so multiple resin inlets would be required. A 1m inlet spacing is applied following discussions in the previous section, from which estimates can be made for the total durations of infusions at different vacuum levels for an equivalent 9m long part. These estimates are displayed together with calculations of average fibre weight fraction and any identified defects that do not meet the acceptance criteria in Table 28 below. Fibre alignment and positioning tolerances are not considered for these initial infusion tests as they are more relevant to later experiments that feature the layup of representative preforms on the demonstrator tool.

Table 28: Evaluation of thin vertical test samples infused at different vacuum levels against process requirements

Process requirement		Experiment		
Name	**Value**	**-0.9 bar**	**-0.7 bar**	**-0.5 bar**
Maximum infusion duration (9m)	8 hours	3 hours	5 hours	10 hours
Laminate fibre weight fraction	65% - 72%	48	45	39
Acceptable defects	See Table 2.	No observed defects	No observed defects	No observed defects

It should be noted that the fibre weight fractions are intentionally lower than the acceptable range due to the setup of the experiment. The laminates consist of 1 ply Saerflow and 1 ply quadaxial reinforcement and are therefore composed of ~50% flow media, which is not representative of the hull shell laminates and significantly reduces the average laminate weight fraction. Therefore, fibre weight fraction is not a critical factor in these initial tests and will instead be considered in greater detail during the more representative experiments that feature later in this chapter. The important conclusions to be taken from this experiment are the achievable infusion heights and predicted infusion durations. Based on this data, -0.5bar is identified as an unsuitable vacuum level and is not considered further in this research. -0.7bar to -0.9bar is therefore identified as a suitable range of vacuum levels for use in further infusion investigations.

4.3.3.2 Effect of hydrostatic pressure

Hydrostatic pressure is expected to gradually reduce the pressure differential across the system as the height from the resin reservoir is increased. This means that upper sections of the preform may take longer to infuse compared to those at ground level. To test this theory, two identical laminates were infused simultaneously at different heights from the resin inlet.

Question: What is the effect of resin reservoir height on the infusion process?

Data acquisition method: Experiment.

The infusions were setup in a similar manner to the previous experiment and were conducted at -0.9 bar vacuum level. For this experiment, the preforms were 1m long and were raised so that the tops of the laminates were 6m from the ground. For one infusion, the resin reservoir was placed at ground level, whilst the other reservoir was raised up 3m from the ground. The difference in height of the two reservoirs equates to a difference in hydrostatic pressure of approximately 0.32 bar. Figure 38 shows the setup for this experiment.

As with the previous experiment, infusion duration is the most important result of this experiment. Based on the results of the previous experiment, fibre weight fraction is not measured in this test as it is not thought to provide any useful data. The parts were inspected after cure and met the defect acceptance criteria. Figure 39 displays the resin flow front progression with time for these two infusions. As predicted, the hydrostatic pressure significantly affects the resin flow rate. The results of this experiment indicate that positioning the resin reservoir on the floor will likely result in a demonstrator infusion duration that far exceeds the 8-hour maximum goal, and that raising the reservoir to at least 3m in height from the ground will solve this issue. However, this may not be practical or safe to do during the demonstrator infusion which will use approximately 1 tonne of resin. Instead, it is proposed that the same effect be achieved by using a resin injection machine that can supply positive pressure, as shown in Figure 40.

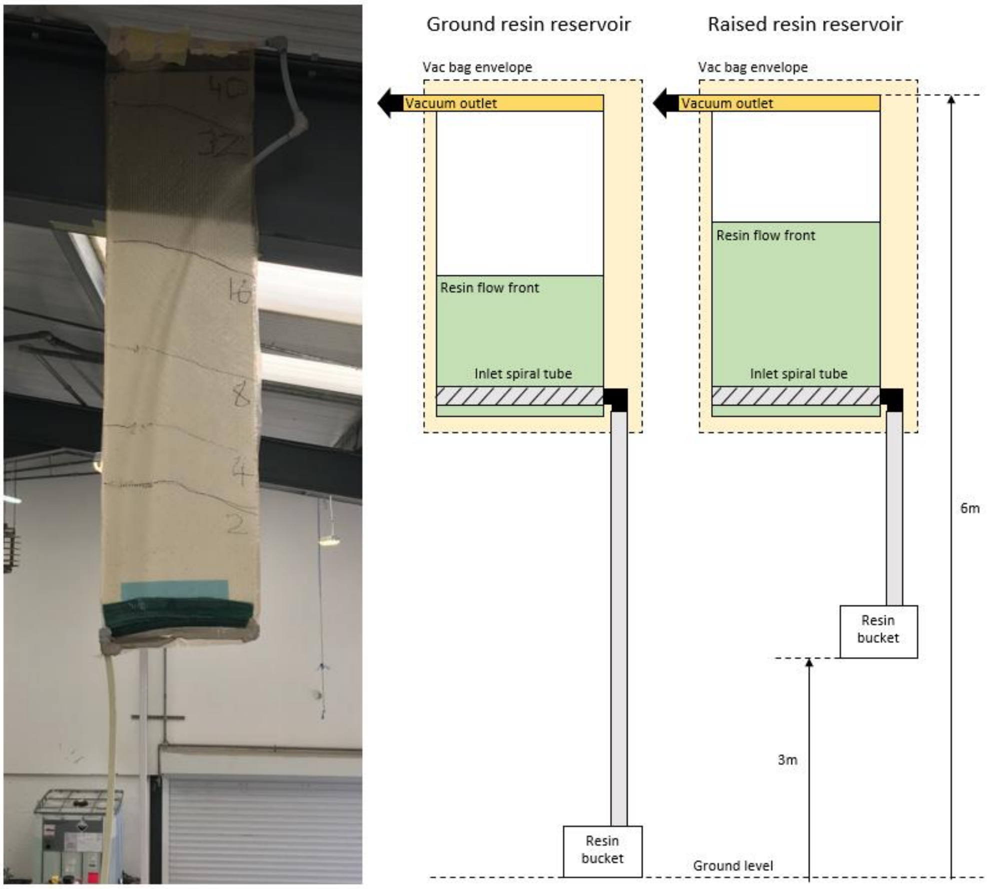


Figure 38: Thin, vertical infusions with varied heights from resin reservoir setup

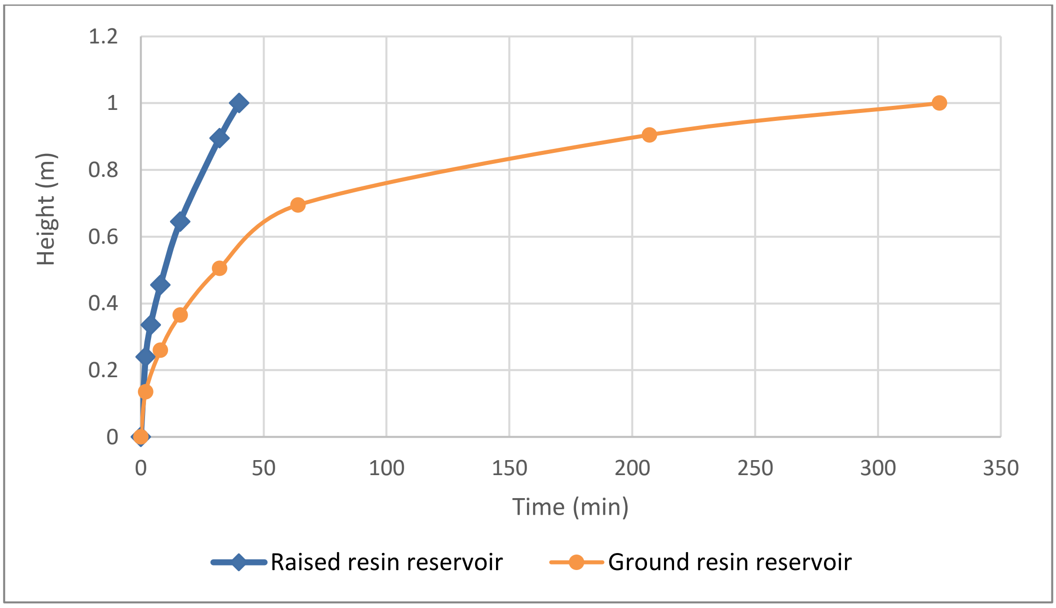


Figure 39: Resin flow front height vs time for thin vertical infusions at different heights from the resin reservoir

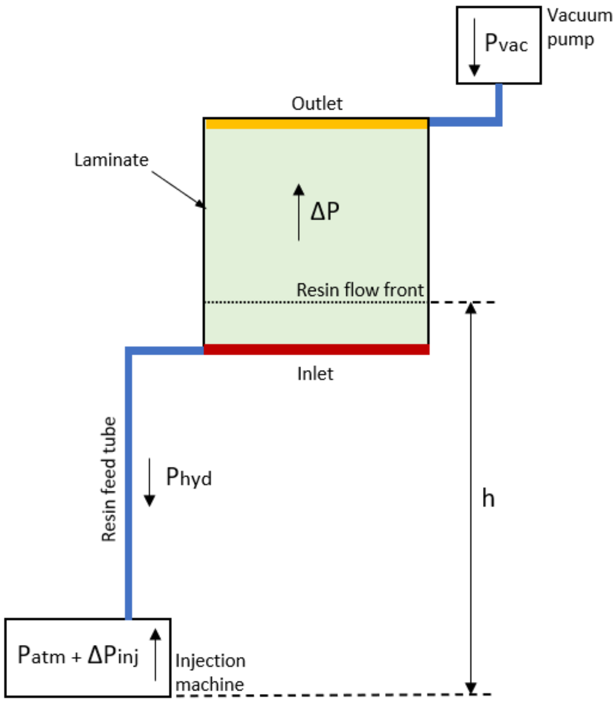


Figure 40: Pressures acting on a vertical infusion with an injection machine

In this revised infusion scheme, there is an additional pressure acting on this system; P_{inj}. The injection machine allows for a positive or negative value of P_{inj}. Equation (17) expresses the revised calculation for the pressure differential across the system.

$$\Delta P = P_{atm} - P_{vac} - P_{hyd} \pm P_{inj} \tag{17}$$

By setting an injection pressure equal in magnitude to the hydrostatic pressure, it is possible to achieve a maximum pressure differential equal to a standard horizontal infusion. The injection machine was not available for testing in this study; however, it is implemented in the infusion strategy and was used during the demonstrator production in chapter 5.

4.3.4 Effect of tool surface

The investigations thus far have featured vertical laminates enveloped by vacuum bags. This is not representative of the demonstrator infusion, which will be conducted on a steel tool. It is believed that the surface adjacent to the laminate surface (either vacuum bag or tool surface) will affect the speed of infusion due to changes in local permeability. The vacuum bag compacts tightly against the laminate surface, filling any small gaps between fibre tows, whilst a tool surface does not. The latter case results in more open channels, and thus a higher local permeability and faster resin flow. It is important to measure this effect because a 6m vertical tool surface was not available during this study (the demonstrator tool would be delivered at a later stage in the project).

Figure 41: Vertical infusion on aluminium tool surface

Question: How does the choice of tool or bag surface effect the infusion process?

Data acquisition method: Experiment.

The previous infusion was repeated on a vertical aluminium tool surface. The laminate was 2.3m in length with three inlets at heights: 0, 1 and 2 metres from the base. A vacuum level of -0.9 bar was applied for this test. Figure 41 shows the setup for this test and Figure 42 compares the measured height vs time for the first 1 metre section with the first envelope bag experiment.

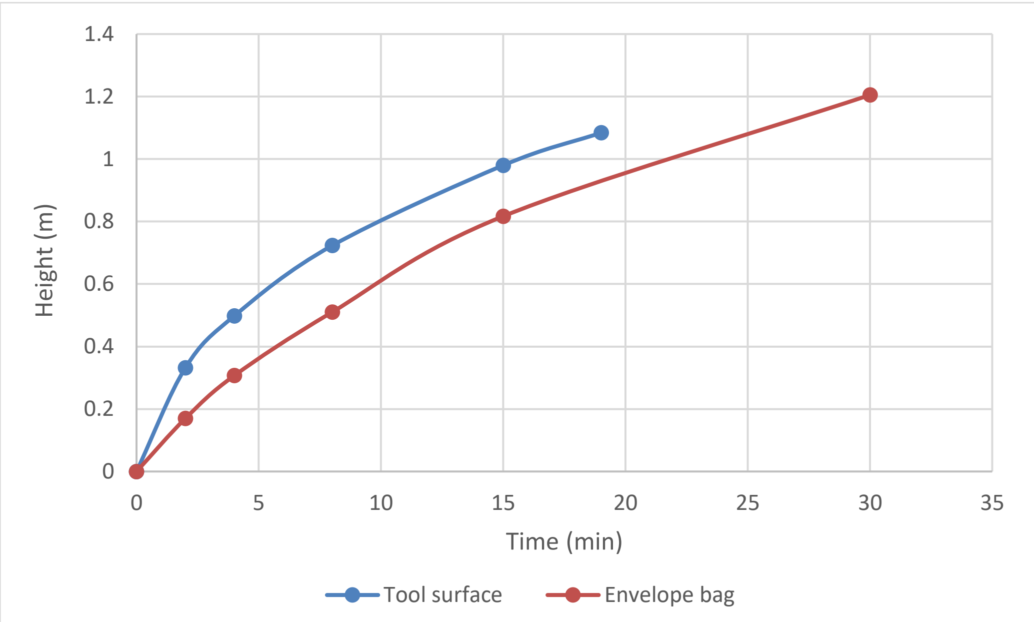


Figure 42: Comparison of resin flow front height vs time for vertical infusions conducted on tool surface and within envelope vacuum bag.

Figure 42 indicates that the tool surface resulted in a slightly accelerated resin flow compared to an envelope bag. This indicates that the demonstrator tool will be beneficial in aiding resin flow, and that the experiments conducted thus far using envelope bags may be conservative. Therefore, the data from this and previous experiments suggests that it is possible to achieve an 8-hour infusion on a vertical tool surface (using thin laminates). It is important to note that whilst this is true for thin laminates, this effect is expected to be much smaller for 200mm thick sandwich panels with 10mm+ thick laminate skins, as the single ply against the tool surface in this case is a much smaller proportion of the overall laminate thickness. Further experiments are required to gain a better understanding of the full-scale demonstrator infusion.

4.3.5 6m vertical infusion trial

The infusion strategy developed thus far was applied to a 6m vertical laminate. The purpose of this test was to determine whether it was possible to infuse up to 6m in height using this strategy.

The experiment was setup in a similar manner to previous trials using the same materials and an envelope vacuum bag hung from a height. The top of the laminate was positioned 6m from the ground, and resin inlets were equally distributed along the length every 1 metre. Two variations of this infusion were conducted; one with a fixed resin reservoir on the ground, and one with a variable reservoir height to alleviate hydrostatic pressures. In the latter infusion, two resin reservoirs were used, one at ground level and one raised to 3m. Both infusions were conducted at 18°C with a vacuum level of -0.7 bar. Freshly mixed resin was periodically supplied to the reservoirs throughout the infusion to avoid premature gelation in the reservoir and laminate where possible. -0.7 bar was selected as this represents the median of the defined vacuum level range. The setup for these infusions is shown in Figure 43 and the results in Figure 44.

The data presented in Figure 44 shows that, for the vertical infusion with the reservoir fixed at ground level, the resin flow rate reduces with increased height due to greater hydrostatic pressures. It was not possible to complete this infusion as the resin flow stopped at approximately 5.7m due to resin gelation. The hydrostatic pressure at this height is approximately 0.63 bar, resulting in a pressure differential of only 0.07 bar. This explains the excessively slow infusion in this region.

The raised reservoir infusion was successful, proving that increasing the height of the reservoir reduces the hydrostatic pressures and increases the resin flow rate. This infusion was split into two halves that theoretically should be identical, and a repeating pattern can be seen in Figure 44 to support this. The raised reservoir significantly increased the resin flow rate in the upper half of the laminate, resulting in a total infusion duration of 282 minutes (4.7 hours), well within the 8-hour limit.

It is also interesting to compare the results of this experiment (Figure 44) with those recorded during the first vertical infusions (Figure 37). Implementing multiple inlets is shown to accelerate the resin flow rate, allowing much greater distances to be infused. More frequent inlets would result in a faster infusion; however, this would likely not be practical from a manufacturing perspective. A compromise must be made between infusion duration and layup/consumables costs. The 1 metre inlet spacing appears to be a good compromise.

It is important to note that the first half of both infusions, whilst theoretically identical, do not perfectly match due to experimental variations. The variations exist due to inlet placement tolerances, permeability variations due to handling and cutting plies and potential distortion of the setup when hanging the laminate vertically from the ceiling. These experimental errors do not negate the conclusions of this study.

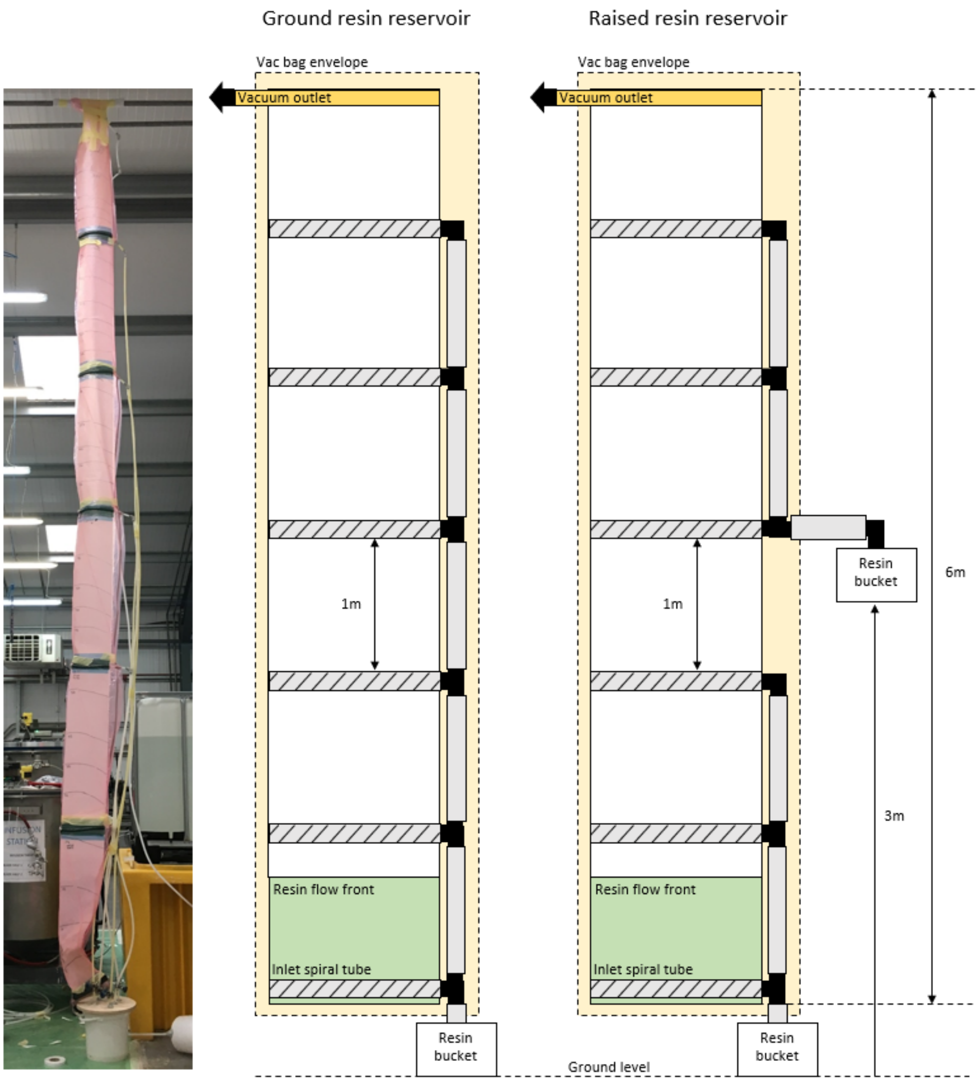


Figure 43: 6m thin vertical infusion setup with and without raised resin reservoir

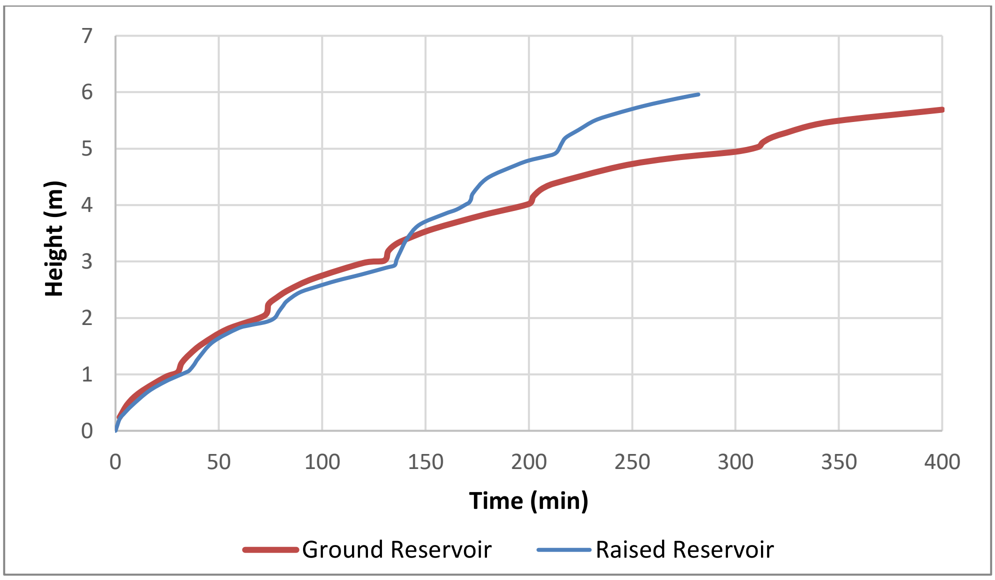


Figure 44: Resin flow front height vs time for thin 6m vertical infusions with and without raised resin reservoir

After cure, the bag was removed, and the part visually inspected. A bright light was also held underneath the part to inspect the quality within the laminate. No notable defects were observed, and the quality of the laminate was in accordance with the defect acceptance criteria. This observation was consistent over the total height of the laminate, with no notable differences between regions of the laminate that were close to or far from the resin inlets.

The laminate was then cut into multiple sections to measure the cross-sectional thickness at various heights. It was hypothesised that there may be a variation in laminate thickness (and hence fibre weight fraction) due to the combination of hydrostatic pressure and the ability of the vacuum bag the freely expand and contract depending on the internal infusion pressure. It is therefore important to quantify this effect as it may affect the demonstrator production.

Question: How does the laminate thickness vary with height for a thin vertical infusion?

Data acquisition method: Experiment.

Figure 45 shows the measured average laminate thickness at various positions up the laminate as a percentage of the maximum thickness. A set of digital vernier callipers were used to take these measurements. The data shows a steady reduction in thickness with height and a clear division between the two halves of the infusion. In each half the laminate thickness reduces by approximately 20% over a 3-metre height from a maximum thickness of 2.5mm. This trend appears to be similar for the lower and upper sections of the laminate, with maximum laminate thicknesses located at the same heights as the two resin reservoirs.

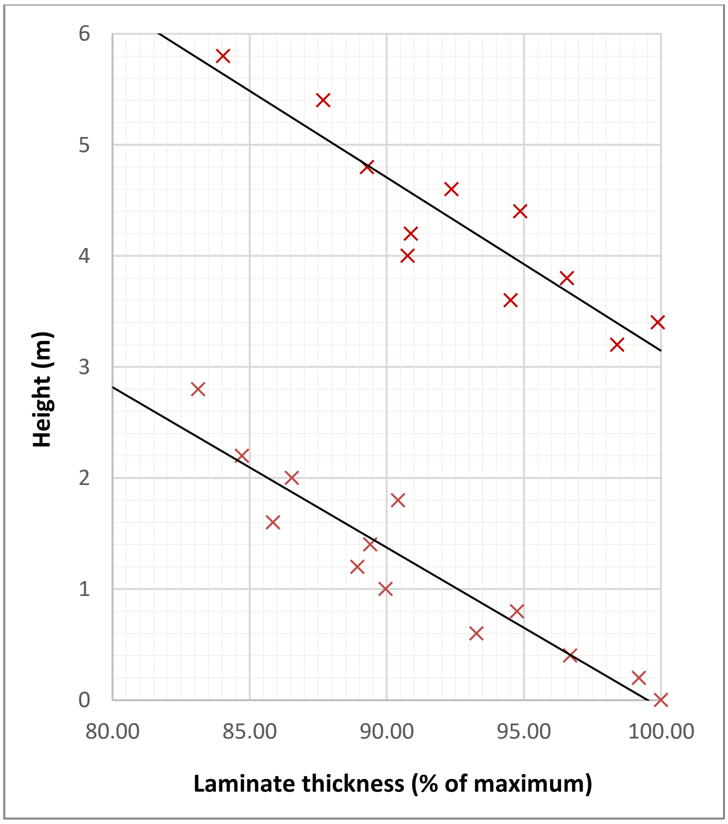


Figure 45: Average laminate thickness vs height for a 6m vertical infusion with a raised reservoir

A return to 100% laminate thickness at 3m in height suggests that the cured laminate thickness is dependent on the pressure differential during infusion, rather than absolute height from ground. It is therefore unlikely that the thickness variation is caused by resin draining downwards after the infusion has completed. It may therefore be possible to control this effect by regulating the pressure differential during the infusion. An injection machine could supply variable injection pressures to achieve this.

The laminate thickness range in Figure 45 (100% to 83%) corresponds to 1.80mm to 1.49mm, or 46% to 51% fibre weight fraction. As discussed for the previous vertical infusions of thin laminates, it is expected that the fibre weight fractions of these initial tests will not meet the requirements outlined in the initial specification (65% to 72%) due to the composition of these thin laminates (unrepresentative ratio of flow media to reinforcement). However, the maximum variation in fibre weight fraction over this test is 5%, which lies within the acceptable range of weight fraction variation (7%). This indicates that thickness variation due to hydrostatic effects may be acceptable, however further tests with more representative laminates and a resin injection machine will be required to confirm this.

Based on the results of this experiment, this 6m vertical infusion configuration is deemed suitable for producing good quality thin laminates in an acceptable timeframe. This configuration will therefore be implemented within more representative tests later in this chapter.

4.4 2D Through-Thickness Infusion of Thick Sandwich Panels

The work in this section aims to further refine the infusion strategy developed thus far by considering the additional complexities of through-thickness resin flow within thick sandwich sections.

> **Question:** What is the most suitable inlet and outlet configuration for infusing large, thick sandwich sections of comparable geometry to the selected case study?
>
> **Data acquisition method:** Structured round-table discussion with experts, supported by experiments where required.

This work focuses on the movement of resin in the through-thickness plane. To remain consistent with the structural design, this work shall only consider foam core sandwich panels with glass reinforcement skins. The sectional thicknesses of up to 275mm makes this work particularly challenging. The resin must fully wet-out both skin laminates, requiring careful placement of inlets and outlets and potentially additional features such as resin flow channels within the preform.

One of the key drivers of this work is the development of a robust process. The infusion strategy should therefore minimise the risk of defects, especially within areas that cannot be easily seen or inspected such as the foam core. It is very difficult to identify defects within sandwich panels of this thickness as typical non-destructive testing (NDT) methods such as ultrasound or X-ray scanning are not suitable for such large, thick structures. An undetected defect is worse than a detected one, so whilst the process must minimise the risks of defects forming, it may also be beneficial to maximise the visibility of any defects that do form.

Several infusion schemes have been devised based upon previous experience and consultation with industry experts. These are described in Table 29 and can be summarised by the following four categories:

1. **In-plane infusions with regular perforations in the foam core.**
   The key driver behind these schemes is to maximise the number of resin flow paths within the foam core by providing a network of interconnected channels in all three major axes. This reduces the chance of dry regions forming in the part.
2. **Modular infusions with localised flow channels.**
   The sandwich structure is divided into discrete, repeated modules that are infused sequentially or in parallel. These schemes rely on controlling the resin flow path and speed with careful placement of resin flow channels throughout the preform.
3. **Separate skin infusions.**
   The infusion of the top and bottom skins can be separated to simplify the infusion process and reduce the risk of lock-offs forming. This allows for simple in-plane infusions of the two skins, although this modification may result in a longer and more expensive process.
4. **Through-thickness infusions.**
   These infusions feature resin flow through the foam core from one skin to the other. The main advantage of this scheme is the significantly shorter duration compared to in-plane infusions.

These schemes are evaluated against the following criteria, which were identified based upon the initial project specification and round-table discussions with experts:

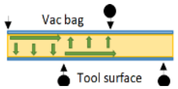
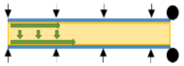
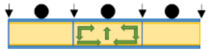
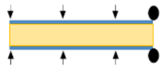
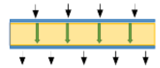
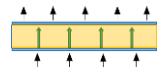
- **Robustness:** The likelihood of process failure or defects forming due to variations in the procedure. An infusion scheme requiring a tightly controlled resin flow path through the structure would be less robust than one that is tolerant to variations. Simpler setups with a minimal number of unique flow fronts may therefore be preferred.
- **Visibility and Accessibility:** All infusion schemes will require some level of manual control, so it is important that the operator can clearly see what is happening during the process. However, only the top surface of the thick sandwich panel is visible, so infusion schemes that are reliant on knowing where the resin flow front is located deep within the section may be difficult to execute. To try and address this, some schemes attempt to accelerate the resin flow through the bottom

skin (which cannot be seen) to minimise the risk of lock-offs in these regions. It is also important that any issues are identified quickly as it may be possible to rectify during the process. For example, the resin flow speed may be throttled, or the opening of inlets delayed to reduce the size of a dry spot. In extreme circumstances additional inlets or outlets may be added during the process.

- **Tool Complexity:** More complex tooling, such as those with embedded flow channels or inlet/outlet ports may be required for some infusion schemes. Whilst these allow for more complex resin flow paths, the capital, maintenance and operational costs will be greater. Simplicity is generally preferred over complexity.
- **Sensitivity to Core Layup:** As outlined in the previous chapter, the thicker foam core sections shall be constructed by stacking 50mm thick foam sheet, similar to brick laying. Layup tolerances may result in gaps between foam sheets where resin can flow freely, potentially race tracking to a nearby outlet. This can cause lock-offs (dry regions that are isolated from the vacuum outlet, and therefore will not infuse). The foam sheets are also supplied with deep cuts (draping slits) to allow them to drape to the curvature of the tool. These provide additional resin flow channels within the foam core that may affect the infusion scheme.
- **Effect on Structural Performance:** Certain infusion schemes implement localised flow channels within the foam core to aid the infusion process. These can produce resin rich regions and local weaknesses within the structure, especially if they are continuous through the sectional thickness. A continuous, uniform structure is preferred.
- **Process Duration:** This is an estimation of the process total duration, including: layup, bagging, infusion, demoulding and tool preparation for the next infusion. The infusion duration is heavily dependent on the direction of resin flow, with through-thickness infusions offering accelerated processes. Some infusion schemes require inlets/outlets and flow channels embedded within the tool surface that must be cleaned after demoulding. Cured resin will be stuck in these features and may be difficult to remove.

Table 29 details the evaluation of all infusion schemes.

Table 29: Evaluation of 2D through-thickness infusion schemes.

Key for diagrams	Scheme 1 - In-plane infusion with regular perforations			Scheme 2 - Modular infusion with localised resin flow channels		Scheme 3 - Separate top and bottom skin infusion		Scheme 4 - Through-thickness infusion	
	A	B	C	A	B	A	B	A	B
Pre-cured laminate Foam core Resin flow path Dry rein-forcement Inlet position Outlet position	Foam core with network of flow channels in-plane and through-thickness (perforations and grid) distributed evenly throughout core. Reversible inlets/outlets positioned across both surfaces. Infusion conducted sequentially between skins going from left to right.	Similar to scheme 1A, however all inlets are positioned on top skin for better accessibility, with a single outlet at the end of the part. More open channels located along bottom of foam core to accelerate flow in bottom skin. Infused from left to right.	Similar to scheme 1B, however additional inlets positioned on bottom skin to aid resin flow on bottom surface. Top and bottom skin inlets are connected to the same resin feed and opened at the same time. Infused left to right with outlets at the end of the part.	Similar to scheme 1B, however the infusion is split into modules with localised through-thickness flow channels. Inlets only positioned on top skin. Resin travels quickly through thickness so that top and bottom skins are infused simultaneously. Infused left to right with single outlet at end of part.	Modular infusion with all inlets and outlets positioned on top surface for better accessibility. Localised through-thickness flow channels supply resin quickly to the bottom skin. Both skins infuse inwards simultaneously towards outlets positioned in the centre of each module, on the top surface. All modules infused simultaneously for a potentially faster infusion.	Skins are infused simultaneously. No through-thickness flow channels separates the skins and results in a simpler infusion process. Both skins infused progressively from left to right.	The infusion is split into to separate parts. Firstly, the bottom skin is infused separately on the tool. The foam is then bonded to the cured bottom skin laminate using adhesive. Finally, the top skin is infused over the foam to create the sandwich panel.	Infusion conducted through-thickness with multiple inlets located across top skin and many outlets on the tool surface. Perforations in foam core provide through-thickness flow paths.	Similar setup to scheme 5A, however infusion is reversed with inlets on tool surface and outlets on top surface.
									
Robustness *(3)*	Resin flows in both in-plane and through-thickness directions. Resulting flow front is potentially complex with a risk of lock-offs throughout. The scheme does not rely on controlling the resin flow path, but instead allows the resin to flow freely, which is beneficial for process robustness.	Similar robustness level as scheme 1A. More uniform flow front moving left to right is expected to reduce risk of lock-offs slightly, however lack of inlets on bottom skin increases risk of localised lock-offs on bottom surface.	More uniform flow front than scheme 1A combined with regular inlets on top and bottom skin results in a robust infusion process. Complete wet-out of each skin is not dependent on through-thickness resin flow, however through-thickness perforations prevent one skin racing too far ahead.	Simple, predictable flow fronts along pre-defined paths. However, process variations may lead to issues as this scheme is dependent on controlling the resin flow.	High-risk process that is very sensitive to variations. Resin flow must be tightly controlled along pre-defined paths. There is a high risk of lock-offs where the flow fronts meet at the centre of each module.	Simple in-plane infusion process for top and bottom skins. No complex through-thickness resin flow due to lack of through-thickness perforations/flow channels. However, this scheme is sensitive to core layup tolerances.	Simple in-plane infusion process for top and bottom skins. No complex through-thickness resin flow as skins are infused separately. However, it will be difficult to control the quality of the adhesive bond between the foam to the bottom skin over such a large surface area.	Theoretically this scheme produces a single resin flow path through the thickness, However, variations in the process may result in faster resin flow in some areas. This can result in complex resin flow paths and lock-offs near the outlets.	Theoretically this scheme produces a single resin flow path through the thickness, However, variations in the process may result in faster resin flow in some areas. This can result in complex resin flow paths and lock-offs near the outlets.
Visibility and Accessibility *(2)*	Inlets and outlets located on bottom skin are not visible, so timing the opening and closing of them is difficult. Any issues/lock-offs on the bottom skin are not seen until after demoulding the hull.	All inlets and outlets are located on the top surface where they are clearly visible, allowing easier control of the process. Any issues/lock-offs on the bottom skin are not seen until after demoulding the hull.	The top and bottom skins are connected, and therefore opened at the same time. If the flow in the bottom skin is always ahead of the flow in the top skin, then visual monitoring of the top skin is all that is required.	Poor visibility of resin flow on bottom skin is a critical issue. Top and bottom skins are disconnected (due to lack of regular through-thickness perforations), meaning one may race ahead of the other. Timing the opening of inlets is therefore very difficult.	Inlets and outlets positioned on top surface for better access. Poor visibility of bottom surface not a critical issue as all inlets are opened simultaneously, so there is a limited level of manual control.	Bottom skin infusion is extremely difficult to conduct due to poor visibility. This leads to high risk of defects.	Visibility for the two skin infusions is very good.	Outlets on bottom surface are not visible, meaning it is difficult to know when the infusion has finished. All inlets are opened together so limited manual control is required.	Outlets completely visible. Fully wet out top surface generally indicates that entire part is completely infused. High risk surface fully accessible for repairs prior to demoulding.
Tool complexity *(2)*	Requires embedded inlet/outlets and flow channels across tool surface, resulting in a complex and expensive tool.	This scheme allows for a smooth, simple tool face with no embedded inlet or outlets.	Requires embedded inlet/outlets and flow channels across tool surface, resulting in a complex and expensive tool.	This scheme allows for a smooth, simple tool face with no embedded inlet or outlets.	This scheme allows for a smooth, simple tool face with no embedded inlet or outlets.	Requires embedded inlet/outlets and flow channels across tool surface, resulting in a complex and expensive tool.	This scheme allows for a smooth, simple tool face with no embedded inlet or outlets.	Requires excessive inlet/outlets embedded across the tool surface, resulting in a complex and expensive tool.	Requires excessive inlet/outlets and flow channels embedded across tool surface, resulting in a complex and expensive tool.
Process sensitivity to core layup *(2)*	Scheme is not very sensitive to race tracking through gaps between core sheets due to regular perforations in foam. Large gaps may cause issues.	Scheme is not very sensitive to race tracking through gaps between core sheets due to regular perforations in foam. Large gaps may cause issues.	Scheme is not very sensitive to race tracking through gaps between core sheets due to regular perforations in foam. Large gaps may cause issues.	The success of this scheme relies on controlling the resin flow within pre-defined paths. Resin race tracking due to gaps between foam sheets would compromise the process.	The success of this scheme relies on controlling the resin flow within pre-defined paths. Resin race tracking due to gaps between foam sheets would compromise the process.	Gaps between core sections will provide open resin pathways through the thickness, eliminating the key benefit of this scheme.	The bonding process is insensitive to gaps between foam core sheets.	Race tracking through gaps in the foam core may lead to localised lock-offs. The large number of outlets on the tool surface should limit this effect.	Race tracking through gaps in the foam core may lead to localised lock-offs. The large number of outlets on the tool surface should limit this effect.
Effect on structural performance *(2)*	This scheme does not feature any significant structural weaknesses.	This scheme does not feature any significant structural weaknesses.	This scheme does not feature any significant structural weaknesses.	Localised resin rich through-thickness flow channels create weaknesses in the structure.	Localised resin rich through-thickness flow channels create weaknesses in the structure.	This scheme does not feature any significant structural weaknesses.	May be difficult to control quality of adhesive bond, resulting in risk of disbonding. Exact effect on structural performance is unknown and beyond the scope of work.	This scheme does not feature any significant structural weaknesses.	This scheme does not feature any significant structural weaknesses.
Process duration *(2)*	Several inlets to layup on top surface and tool maintenance required to clean cured resin from embedded inlets.	Multiple inlets to layup on top surface, although minimal tool maintenance required.	Multiple inlets to layup on top surface and extensive tool maintenance task to removed cured resin from embedded flow channels and inlets on tool surface.	Multiple inlets to layup on top surface, although minimal tool maintenance required.	Multiple inlets and outlets to layup on top surface, however infusion duration is significantly reduced and minimal tool maintenance is required.	Multiple inlets to layup on top surface and extensive tool maintenance task to removed cured resin from embedded flow channels and inlets on tool surface.	Two infusions doubles the overall duration. Additional bonding step will take a long time due to large bonding area.	Multiple inlets to layup on top surface and extensive tool maintenance is required after demoulding. However, infusion duration is significantly reduced.	Multiple outlets to layup on top surface and extensive tool maintenance is required after demoulding. However, infusion duration is significantly reduced.
Total Score	24	30	27	24	22	16	18	24	28

The total scores presented at the bottom of Table 29 can be used to quickly disregard the most unsuitable schemes with the lowest scores. Infusion schemes 2B, 3A and 3B are the lowest scoring options. Scheme 2B is not robust enough for commercial application, whilst schemes 3A and 3B cannot be easily implemented in practice. Schemes 1A, 2A, 3A and 4A are all limited by the poor visibility and accessibility of the bottom skin. This is a key weakness as all these schemes feature some level of manual control which is dependent on observing the resin flow progression in the bottom skin. Flow sensors could theoretically be implemented to overcome this, however the numbers required for a ship hull and the associated costs mean that this is not a commercially viable option.

The total scores indicate that infusion scheme 1B is the best overall compromise across the various evaluation criteria. This scheme is also directly compatible with the infusion strategy previously developed for thin vertical laminates. Scheme 4B features the second highest score, however its key weakness (tool complexity) is predicted to add further cost and complexity to both the demonstrator and 75m hull shell production. It may also be difficult to combine this scheme with the infusion strategy previously developed for thin vertical laminates. Scheme 1C is presented with the third-highest score and is thought to be the most robust option of all schemes considered. Whilst it suffers from the same issue of tool complexity as Scheme 4B, it appears to be far more compatible with the infusion strategy previously developed for thin vertical laminates. This comparison of different schemes highlights the potential for further improvement. Combining schemes 1B and 1C may therefore be an effective approach to address the high risk associated with the demonstrator manufacture within this research project. Both schemes are investigated in further detail using representative experiments in the following section.

4.4.1 Sandwich panel infusion trials

The previous evaluation methodology supported by industrial knowledge and experience has identified two infusion schemes that are compatible with the requirements and challenges of this case study. This section details two representative experiments that were conducted to further refine the infusion strategy developed thus far. These tests investigate the compatibility of the infusion schemes with the selected materials, using test pieces that are representative of the thickest sandwich region (SP1) of the demonstrator. This region is thought to be the worst-case through-thickness sandwich infusion due to its greater thickness and complexity. It is assumed that an infusion strategy capable of successfully producing high quality sandwich sections representative of SP1 will also be capable of producing thinner sandwich regions (SP2 & SP3) to at least the same level of quality. This assumption enables a reduction in the total number of experiments conducted and better supports the rapid development approach. This assumption is based upon experience and will be verified in later trials.

Two sandwich panel preforms of 1m length and 0.2m width were created. 1m length was selected to represent the 1m spacing between inlets that was determined in the previous section. Both sandwich preforms were constructed to be representative of final demonstrator (SP1 section). The 200mm thick foam cores consisted of 4 layers of 50mm thick foam sheets, with 1 ply of Saerflow between them. Each laminate skins were laid up according to the stacking sequence: [Saerflow, $Quadaxial_{10}$, Saerflow, $Quadaxial_{10}$, Saerflow]. Both sandwich panels were laid up using the selected materials, however due to a shortage of Armacell foam core, the infusion trial for scheme 1C used Airex T92.130 foam instead. Both types of foam were closed cell PET with identical density perforation pattern, so this change is not though to affect the infusion results. Figure 46 and Figure 47 show both experiments mid-infusion. Scheme 1B (Figure 46) was setup with a single resin inlet on the top skin, whilst scheme 1C (Figure 47) was setup with resin inlets on both top and bottom skins.

Figure 46: Scheme 1B infusion trial

Figure 47: Scheme 1C infusion trial

Figure 46 and Figure 47 clearly show that scheme 1C results in a more uniform flow of resin across the sandwich sectional thickness. Both infusions were left to continue until resin gelation occurred. Scheme 1C achieved a successful infusion after 1 hour, with fully wet-out skins and no visible dry areas. An equivalent 9m long section with 9 inlets every 1m is therefore estimated to take 9 hours to infuse, slightly longer than the 8-hour goal. However, this simplistic estimate does not account for gravity effects/vertical alignment or changes in sectional composition/thickness, so a more representative test would be required to accurately determine the demonstrator infusion duration. However, this test indicates that the duration of this infusion is somewhat comparable with the 8-hour infusion goal, and therefore should not be neglected. The part was visually inspected after cure, and no notable defects were detected within the laminates that lied outside of the allowable defect range. All regions of the foam core were fully wet-out with resin. The thicknesses of the skin laminates were measured and used to calculate fibre weight fractions for the top and bottom skin of 67% and 69% respectively. These values lie within the acceptable fibre weight fraction range (65% to 72%).

The Scheme 1B infusion did not finish after 4 hours, leaving approximately a 150mm dry region at the end of the part. This significant defect far exceeds the allowable 9.5mm maximum diameter for dry spots defined in the defect acceptance criteria. The quality of this specimen is therefore deemed unacceptable and the infusion scheme unsuitable with the selected materials. It is believed that the primary cause of this issue is an insufficient resin flow through the sandwich thickness to the bottom skin. It is thought that this infusion scheme could be made to work by implementing larger perforations in the foam core. However, such perforations are not available within the standard product range offered by material suppliers and would therefore add further cost and complexity to the manufacturing process. Furthermore, the success of the infusion being highly dependent on through-thickness flow channels would lead to a higher sensitivity to layup variation (channels within different foam layers may not align due to positioning tolerances and/or movement of the preform). This would ultimately reduce the robustness of the manufacturing process. For this reason, infusion Scheme 1B is considered unsuitable for this rapid development approach. Scheme 1C is therefore selected, however further refinement is required to address the tool complexity concerns.

4.4.2 Proposed infusion scheme

In this section a modification to Scheme 1C is proposed in which the flow channels are relocated from the tool surface into the foam core to address the tool complexity issue. All other features of the infusion are maintained based upon the success of the Scheme 1C infusion trial. Figure 48 shows the proposed final infusion scheme for the thick sandwich section.

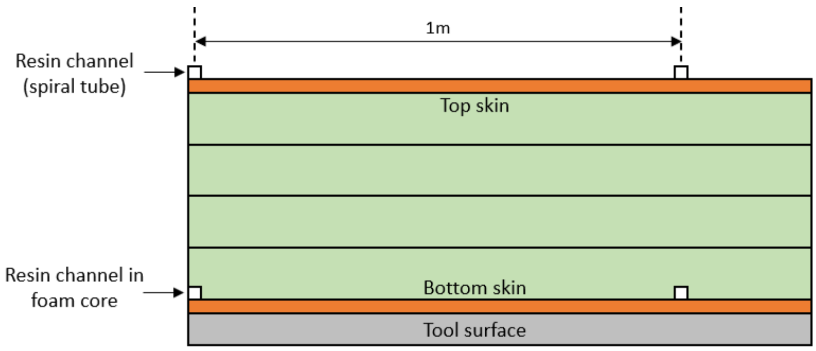


Figure 48: Proposed infusion scheme for 2D thick sandwich panels

Parallel resin channels supply resin to the top and bottom laminate skins simultaneously. These channels are located every 1 metre along the preform, a parameter that was determined in the previous chapter. Unlike with infusion scheme 1C, the resin flow channels embedded in the tool surface have been moved into the base of the foam core. This significantly reduces tool complexity (and therefore process cost and duration) as machining channels in the foam core is much easier and affordable within this research project. These channels are 10x10mm in cross sectional area to be consistent with the 12mm diameter spiral tube used on the top skin.

The experimental results in this section indicate that a demonstrator infusion featuring this through-thickness sandwich infusion scheme could meet the relevant process requirements (Table 30).

Table 30: Evaluation of through-thickness sandwich infusion scheme against relevant process requirements

Process requirements		**Proposed scheme**
Name	**Value**	**Value**
Maximum infusion duration (9m)	8 hours	Approx. 9 hours
Laminate fibre weight fraction	65% - 72%	67% - 69%
Acceptable defects	See Table 2.	No observed defects

Whilst the 9-hour estimated duration slightly exceeds the 8-hour goal, it is important to note that this is a simple estimate and could vary when applied to a full-scale piece representative of the hull shell. Further investigations are required to determine the duration of more representative infusions.

It is also important to note that this proposed infusion scheme is only suitable for the production of the full-scale demonstrator and would not be compatible with a 75m long hull shell. This is because the flow channels within the foam core are only accessible along the sides of the 2.5m wide demonstrator and would be completely sealed within the continuous 75m hull preform. As outlined at the start of this chapter, this work will focus on the product of the demonstrator as the primary goal. This strategy is therefore taken forward, and further refinement for compatibility with a 75m hull shell is left as future work.

This work concludes the development of a baseline 2D infusion strategy for thick sandwich panels. This infusion scheme will now be combined with the previous infusion scheme for thin vertical laminates and applied to larger, more representative trials.

4.5 3D Vertical Infusion of Thick Sandwich Sections

This section investigates the compatibility of the two previous 2D infusion schemes when combined to produce a vertical, thick sandwich panel. A representative vertical sandwich infusion was conducted to investigate three key areas of concern:

- **Gravity effects on the through-thickness resin flow:** Does the resin flow path and/or speed within the thick sandwich preform change significantly when aligned vertically?
- **Layup tolerances and race tracking:** There will inevitably be gaps between the foam core sheets that may allow the resin to race track up the preform. How does this effect the infusion process and quality of the part? The robustness of this strategy has been demonstrated on smaller horizontal sandwich panels, but not yet at a larger scale.
- **Inlet spacing:** An inlet spacing of 1 metre has been shown to be sufficient for all previous trials. Will this setup result in a sufficient resin flow speed when applied to a large, vertical sandwich panel with thick laminate skins and foam core?

In this investigation a 2m long, 1m wide, 120mm thick sandwich panel (100mm thick core with 10mm thick laminate skins) was infused vertically in the 2m direction. The laminate skins were laid up according to the stacking sequence: [Saerflow, Quadaxial_{10}, Saerflow]. The sectional thickness of this trial was chosen to representative SP2; the thickest vertically inclined sandwich panel featured in the demonstrator design. The inlet configuration is identical to the scheme in Figure 48. This trial was conducted on a vertical tool surface to be representative of the final demonstrator infusion. Figure 49 shows the completed infusion and Figure 50 shows the flow front progression with time. Five sets of data are presented in Figure 50 representing the flow front progression along five vertical lines on the preform, labelled A, B, C, D and E in Figure 49. Lines A and E are located on the side faces whilst B, C and D are located on the front face.

The 100mm thick foam core was constructed by stacking 2 layers of 50mm thick Armacell GR135 foam core. The foam sheets used in this trial were 0.5m wide by 1m long, so four foam sheets were required in each layer to create the $2m^2$ preform area. 16 foam sheets were used in total for this experiment. The green lines in Figure 49 indicate the joins between these foam sheets. Each foam block was prewrapped with Saerflow prior to layup. The presence of Saerflow between core faces improved resin wet-out and bonding between core sections. All foam sheets were supplied with infusion channels, draping slits and through-thickness perforations as outlined in chapter 3. The infusion channels were aligned with the 2m length of the preform. In this experiment the term “inner skin” refers to the visible front face, whilst the “outer skin” refers to the hidden laminate against the tool surface.

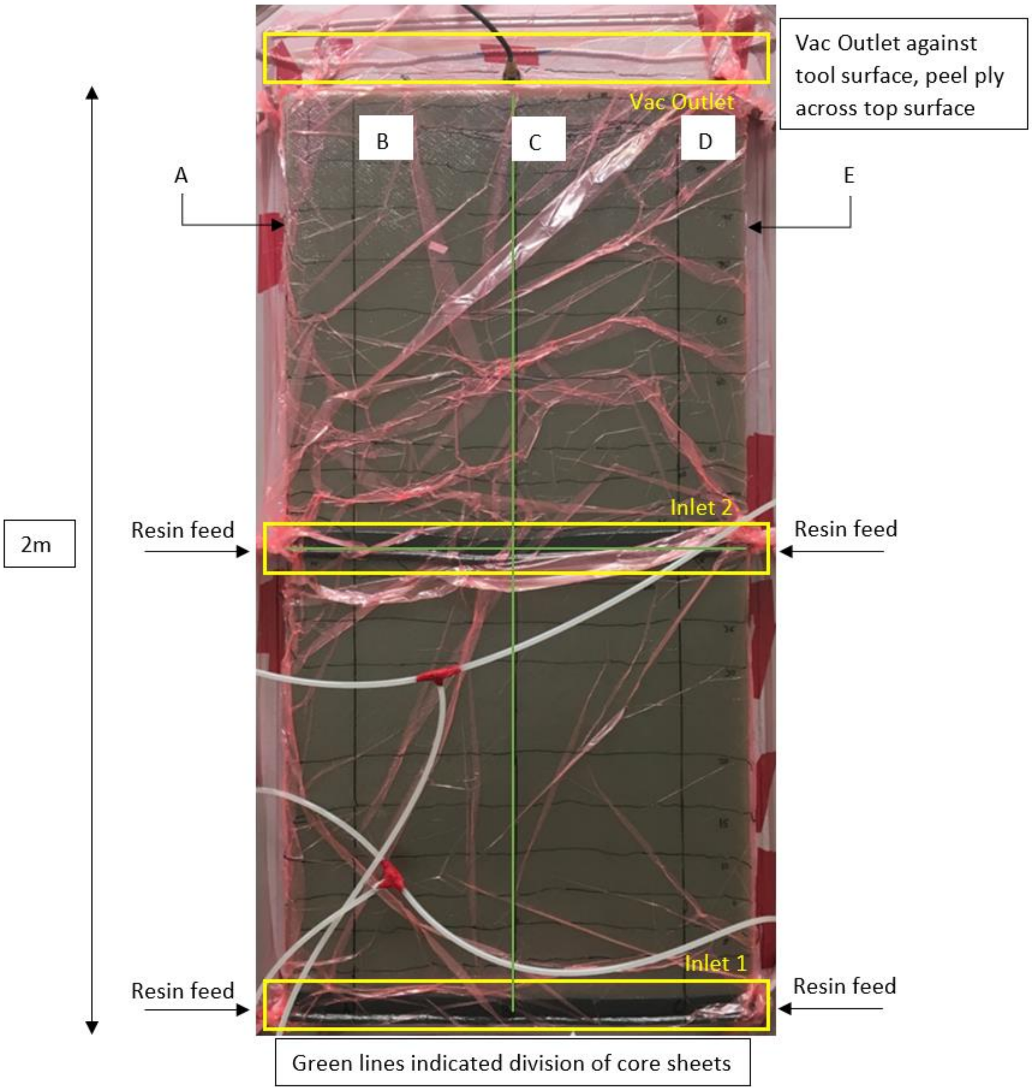


Figure 49: Vertical sandwich infusion trial

Figure 49 shows the two resin inlets: inlet 1 and inlet 2 at heights 0m and 1m respectively. Each inlet consists of a visible spiral tube on the inner skin and a hidden resin channel within the foam core adjacent to the outer skin, as outlined in Figure 48. Inlet 1 was opened at the start of the infusion (time = 0 minutes) inlet 2 was opened 55 minutes later, when the visible flow front on the front face had travelled 200mm past the spiral tube at inlet 2. The preform was fully infused (except one lock-off) after 90 minutes, taking approximately 45 minutes per 1m stage. This is comparable to the 35-40 minutes per 1 metre stage for the first two metres of the thin vertical infusion (Figure 44).

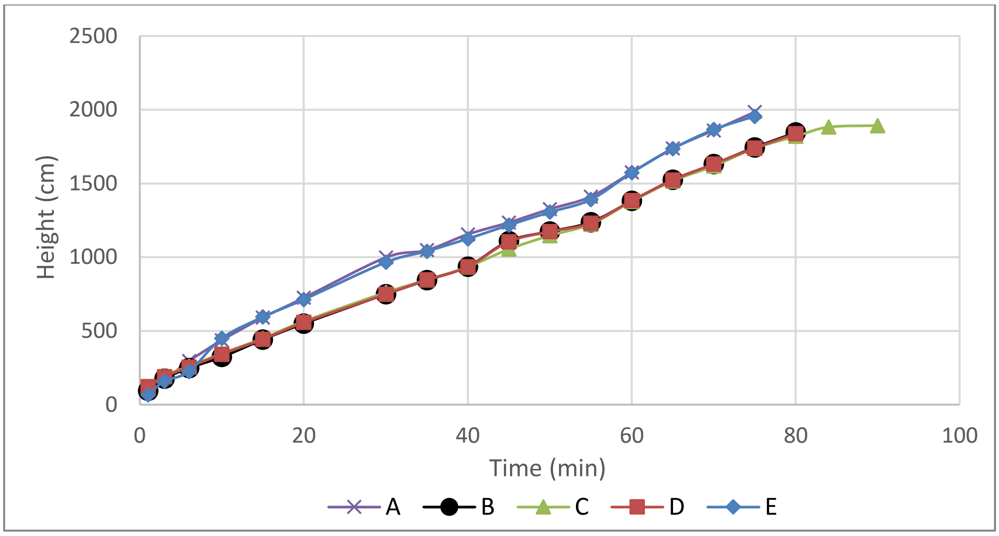


Figure 50: Flow front progression vs time at five locations on vertical sandwich infusion trial

Figure 50 shows that the flow front progression is consistent across the width of the panel (lines B, C and D). The sides of the panel (lines A and E) infused slightly faster than the front face, likely due to the difference in average permeability between the two areas. The average permeability of the side face (1 ply of Saerflow) is much higher than that of the laminate skin (2 plies of Saerflow and 10 plies of quadaxial). Figure 51 shows this effect during the infusion process. The accelerated resin flow up the sides of the preform was also found to occur through the vertical Saerflow plies between the foam core sheets. The resin within these Saerflow plies therefore reached the top of the panel before the resin in the laminate skins. Towards the end of the infusion, a second flow front could be seen progressing downwards from the top surface, originating from the Saerflow plies in the foam core and eventually meeting the primary flow front and creating a lock-off as shown in Figure 52. Figure 53 shows a visual depiction of this process. The infusion was left to continue until resin gelation, however a dry region remained in the cured laminate as shown in Figure 54.

Figure 51: Resin progressing faster up sides than on the inner skin

It is therefore thought that this dry spot is a direct result of the resin flow paths at the top of the sandwich panel, which are influenced by the geometry of the top of the part. It should be noted that the top of the demonstrator features a very different geometry to this (i.e., a gradual monolithic taper). It is thought that this gradual monolithic taper will produce a different resin flow path compared to the open-ended sandwich panel in this test. It is therefore concluded that this defect is a product of this test and is not representative of the demonstrator. In retrospect, implementing a tapered monolithic region at the top of this sandwich trial may have resulted in a more representative test, although it would have significantly increased material and labour costs. Furthermore, the design details of this joint 3 monolithic region were being refined when this test was conducted.

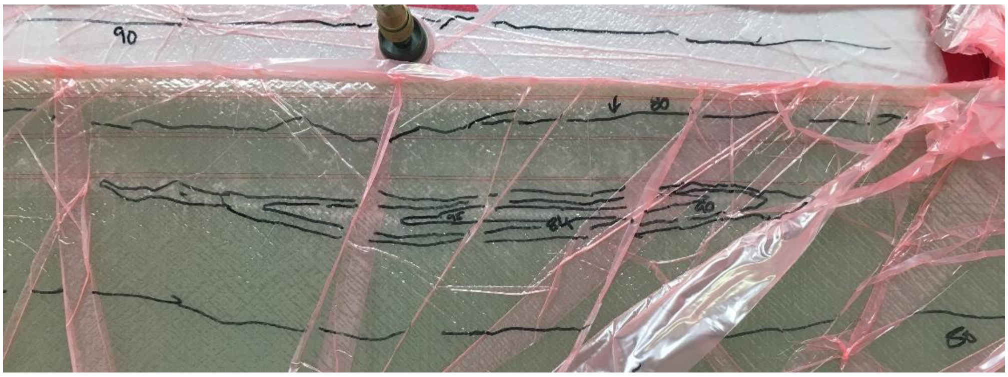


Figure 52: Lock-off forming at the top of the vertical sandwich infusion

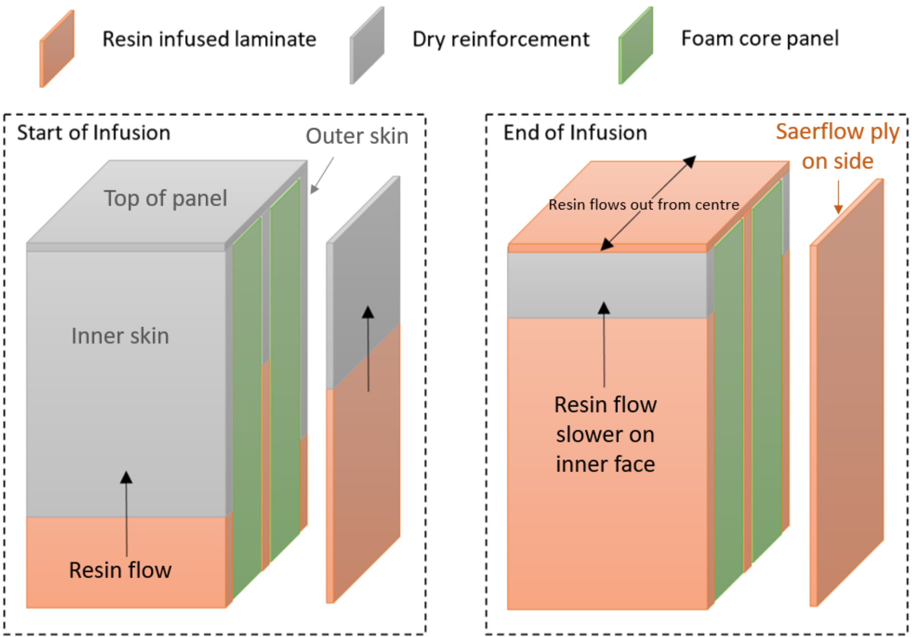


Figure 53: Visual depiction of resin progression through vertical sandwich panel infusion

A section of the panel was cut out after cure to inspect the internal quality of the sandwich section and skin laminates. This cut section is shown in Figure 54. The large dry spot was the only notable defect in the part, which exceeded the 9.5mm acceptable maximum diameter. Despite this defect, the remainder of the section appeared fully wet-out with resin (including internal channels within the foam core). Table 31 evaluates this infusion against the relevant process requirements.

Figure 54: Cross section of cured vertically infused sandwich panel.

Table 31: Evaluation of thick, vertical sandwich infusion against relevant process requirements

Process requirements		Proposed scheme
Name	**Value**	**Value**
Maximum infusion duration (9m)	8 hours	Approx. 7 hours
Laminate fibre weight fraction	65% - 72%	62%
Acceptable defects	See Table 2.	Large dry spot >9.5mm diameter

Based upon the 90-minute infusion duration for the 2m vertical section, a 7-hour infusion estimate is made for an equivalent 9m section. This estimated duration is less than the 8-hour goal. The average fibre weight fraction for this piece is lower than the acceptable range and the previous sandwich test samples. It is thought that this is primarily due to a combination of the following two factors:

- Previous infusion trials were small, so plies could be laid up by a single person and compacted down by hand easily. This test piece required two people to lift and place the 2x1m plies onto the tool. Due to the size of the part and height of the tool surface, it was difficult to reach the laminate skins to manually compact the plies.
- The part was left under vacuum for 4 hours prior to infusion. For comparison, previous infusion trials were left under vacuum for 8 hours. This shorter vacuum duration was a result of time constraints within the project.

It is thought that the combination of these two factors resulted in a slightly lower level of ply compaction at the time of infusion, and thus a lower fibre weight fraction. As the fibre weight fraction is only slightly lower than the acceptable range, it is thought that addressing these two issues in future trials will raise the fibre weight fraction to an acceptable level. To do this, it is proposed that samples be held under vacuum for at least 8 hours (overnight if possible), and that a dedicated layup tool is developed to layup and compact larger plies over areas of the tool that are difficult to access (see Section 5.4.3 for further details). Despite the two minor issues discussed above, this infusion trial was an overall success, indicating that the chosen infusion scheme could be used (with minor modifications) to produce a demonstrator that meets the project requirements.

4.6 3D Infusions of Thick Monolithic Sections

One of the major challenges of this project is the successful infusion of the 275mm thick monolithic keel at the base of the demonstrator. This section is approximately 0.5m long by 2.3m wide. Based upon the infusion scheme that has been developed in the previous sections, the demonstrator infusion will start at this monolithic section. The infusion strategy for this monolithic keel must therefore be compatible with the previously defined infusion scheme for the sandwich panels.

> **Question:** What is the most suitable inlet and outlet configuration for infusing large, thick monolithic sections of comparable geometry to the selected case study?
>
> **Data acquisition method:** Experiment.

The greatest challenge in infusing such a large, thick monolithic laminate is ensuring that resin fully penetrates deep within the centre of the section within a reasonable time frame. Based upon a combination of previous experience, and the size, geometry, and composition of the monolithic keel relative to the entire demonstrator, it is initially estimated that an approximate keel infusion duration of 60 minutes would be required to achieve the 8-hour total infusion duration goal. The results of the following experiments will determine whether this infusion duration is possible with the selected materials.

As discussed in previous sections of this chapter, the simplicity and uniformity of the resin flow front is determined to be a key factor in generating a robust and reliable infusion process. The experiments in this section will therefore aim to create a uniform resin flow front though the monolithic preforms. Within a thick, monolithic preform block, resin may travel in three dimensions; in-plane (x, y) and through-thickness (z). A uniform resin flow front may be produced by promoting resin flow in one dimension whilst minimising flow in the remaining two dimensions. This section considers two approaches for creating a uniform resin flow front within a monolithic brick preform: an in-plane infusion along the fibre direction and a through-thickness infusion. In-plane infusion perpendicular to the fibres is not considered in this study as it is deemed incompatible with the infusion strategy developed this far. This approach could be investigated in future studies if the designers wish to change to layup orientation of the monolithic keel from keel-to-gunwale to bow-to-stern. To reduce development time and costs, this study will focus on the demonstrator manufacture specifically. The two selected infusion strategies are explained in further detail below:

- **In-plane infusion:** A large resin inlet is positioned along the end face of the monolithic keel to create a flow of resin in the in-plane direction throughout the cross section. Flow media is a critical element of this infusion strategy, as it allows for improved resin flow without the need for dedicated flow channels within the laminate (which will negatively impact structural performance).

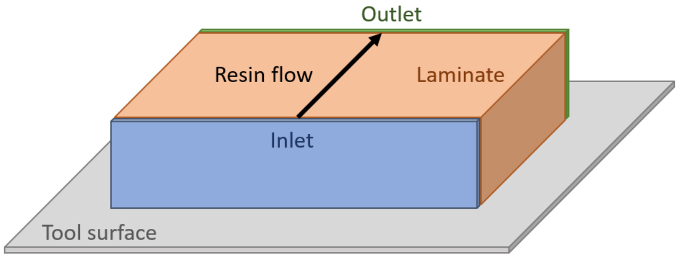


Figure 55: In-plane infusion strategy for thick monolithic laminates

- **Through-thickness infusion:** A large resin inlet is positioned across the bottom face of the monolithic keel to create a flow of resin in the through-thickness direction. Flow media is not effective in this scheme as it only accelerates the in-plane resin flow.

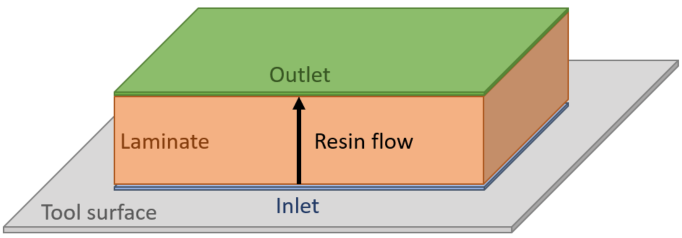


Figure 56: Through-thickness infusion strategy for thick monolithic laminates

An in-plane infusion is preferred as it is more compatible with the previously defined in-plane infusion scheme for the thick sandwich panels. A through-thickness infusion of the monolithic keel conducted adjacent to an in-plane infusion of a sandwich panel would likely cause complications with the two resin flow fronts. Table 27 and Table 3 in the previous sections also highlight the limitations with through-thickness infusions at this scale. Even so, it is still important to understand the strengths and limitations of both infusion schemes when applied to thick monolithic laminates constructed from the selected materials. Two infusion trials were therefore conducted to investigate each infusion strategy in further detail. The selected materials (Albidur 3.2 VE Hull, Saertex glass quadaxial reinforcement and Saerflow flow media) were used for both infusions.

4.6.1 In-plane infusion of thick monolithic laminates

A 220mm thick monolithic laminate was infused on a horizontal tool surface in the in-plane direction. 254 plies were laid up according to the stacking sequence: [[Saerflow, Quadaxial$_{10}$]$_{23}$, Saerflow]. The preform was 500mm in length by 400mm in width and featured a chamfered edge at one end. The preform dimensions and chamfer angle were determined based upon a previous design iteration, as the part was originally planned to be used in a later infusion trial. However, further iterations of the hull design meant that this section was not used.

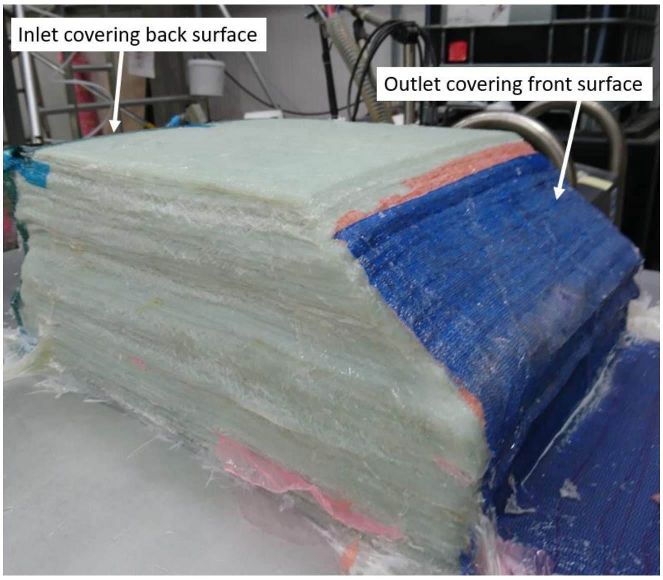


Figure 57: Cured monolithic laminate infused in the in-plane direction

The resin inlet and vacuum outlet were made up of spiral infusion tube connected to blue flow mesh, as shown in Figure 57. The inlet and outlet covered the entirely of the back and front face of the monolithic preform, respectively. The part was left under vacuum overnight prior to infusion. During the infusion, a uniform flow front progressed across the length of the preform from the inlet to the outlet. The flow fronts on the top and side surfaces appeared to progress at the same speed. Due to the lack of localised resin race-tracking up the sides of the part, it is believed that this 400mm wide infusion is representative of the keel featured in the 2.3m wide demonstrator. The infusion completed after 47 minutes. This lies within the 60-minute initial estimate required to achieve the 8-hour infusion goal.

The monolithic laminate was inspected after cure. No notable defects were observed, and the quality was in accordance with the defect acceptance criteria. The part was too thick to be cut easily, therefore only the external surface quality of the laminate was observed. The average fibre weight fraction was calculated as 68.8%, which lies within the acceptable range of 65% to 72%.

Figure 57 shows how the side faces of the cure monolithic block are uneven due to movement of plies during the layup and vacuum bagging procedure. The maximum variation in lateral position of the edges of the reinforcement plies was measured as 15mm. This exceeds the +/-10mm positional tolerance outlined in Table 24. It was observed that the monolithic preform was slightly unstable during the layup and bagging procedure, and that the stack of plies could slide laterally under moderate force (i.e., pushing on the preform during vacuum bagging) and deform the preform. This effect appeared to become more sever as the height of the laminate increased. A modification to the layup method is therefore required to avoid this effect occurring in the demonstrator manufacture. Dividing the thick monolithic preform into multiple thinner sections and applying vacuum compaction to each laminate separately prior to assembling them to form the final monolithic laminate may be an effective approach to tackling this issue. This is explored in further detail in Section 5.7.2.

The results of this test indicate that an in-plane infusion of the monolithic keel is possible for the demonstrator production using these materials.

4.6.2 Through-thickness infusion of thick monolithic laminates

A monolithic brick laminate of 200x200mm area by 100mm thickness was infused on a horizontal tool surface in the through-thickness direction. The laminate consisted of 120 plies of Saertex quadaxial reinforcement. No flow media was incorporated into the layup as it does not provide any significant benefits for through-thickness resin flow. To ensure a more even resin flow front up the block, the laminate was laid up on top of a 15mm thick Nomex honeycomb to create a large resin reservoir. 6 plies of blue flow mesh were positioned underneath honeycomb against the tool surface to provide a flow path between the honeycomb reservoir and inlet spiral. The inlet spiral was positioned in a ring around the base of the layup. The part was left under vacuum overnight prior to infusion. This setup is shown in Figure 58.

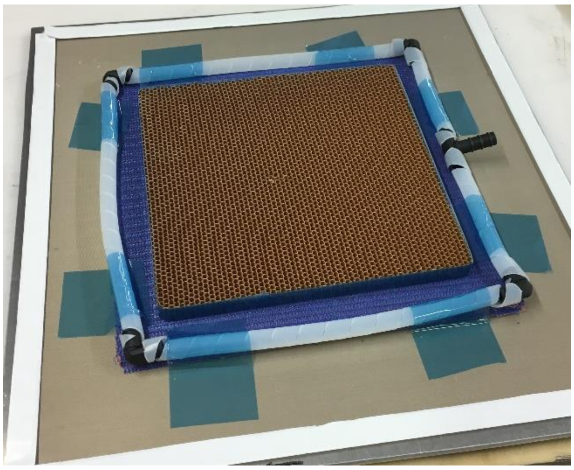


Figure 58: Inlet configuration for through-thickness monolithic infusion trial

Figure 59 shows the infused block. A uniform flow front moved up the sides of the monolithic block during the infusion. The was no evidence of race tracking or edge-effects during the infusion, indicating that this test would be representative of a wider part (such as a 100mm thick, 2.3m wide monolithic keel). The infusion completed after 54 minutes. Whilst this lies within the 60-minute preliminary estimate required to achieve the 8-hour infusion goal, it should be noted that this test piece does not represent the full thickness of the keel. Therefore, the duration of a through-thickness infusion of the 275mm thick monolithic keel is expected to far exceed 60 minutes.

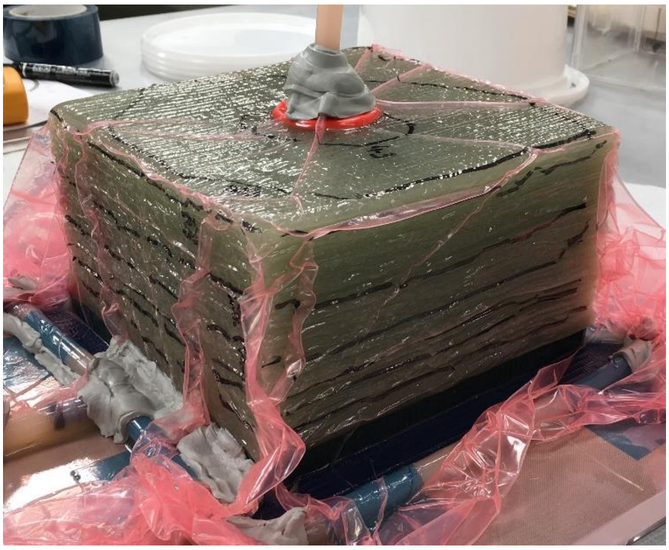


Figure 59: Monolithic block laminate infused through-thickness

After cure, the laminate was demoulded and cut up for inspection. Figure 60 shows the cross section of the laminate, the quality of which was in accordance with the defect acceptance criteria, except for a small line of dry spots (1-2mm diameter) which are highlighted in red. Whilst these dry spots are all smaller than the defined maximum acceptable diameter of 9.5mm, the frequency of these defects and proximity to one-another far exceeds the acceptable limit of 1 defect every 10 inches. This part therefore fails to meet an acceptable level of quality defined in the project specification. However, these dry spots are located exactly where a thermocouple was placed to monitor internal temperatures. Therefore, it is thought that these dry spots were created when the thermocouple was removed from the part. No thermocouple will be used in the demonstrator, so these defects are ignored, and the quality of the part deemed acceptable. The average fibre weight fraction of the part was calculated as 74%, which actually exceeds the acceptable range of 65% to 72%. The fibre weight fraction of this sample is much higher than others produced thus far because no Saerflow plies were incorporated into the layup. These plies lower the average fibre weight fraction due to their resin rich nature.

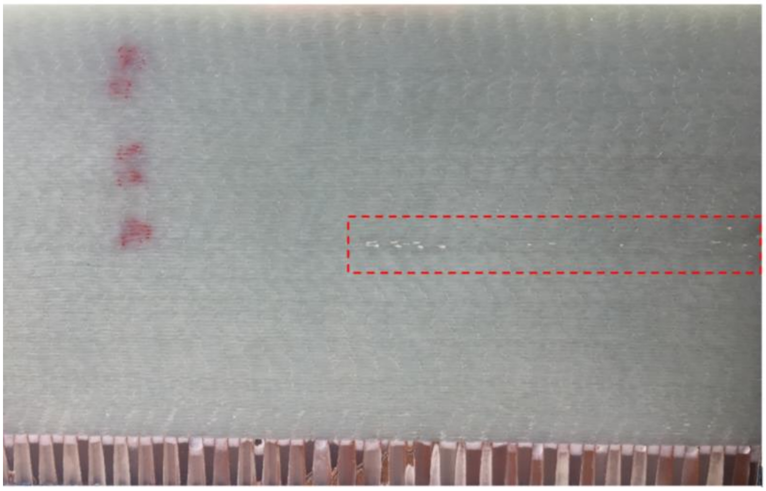


Figure 60: Mid-section of cured 100mm thick monolithic block

A thermocouple was positioned in the centre of the laminate to record the peak exotherm temperature during resin cure. After the infusion had completed, the block was wrapped in insulation foam on all four sides and then left to cure. The insulation limits heat loss to replicate a much larger monolithic section similar to the final demonstrator. Figure 61 shows the recorded temperature vs time at both the laminate core and top surface. The peak core temperature was 96.2°C and is a similar level to typical post-cure temperatures. It is therefore not thought that the exothermic reaction will have a negative effect on the structural properties of the laminate.

The data from this test indicates that a through-thickness infusion of the monolithic keel is unsuitable for the demonstrator production. Not only is the infusion duration predicted to far exceed the defined goal, but practical implementation of this scheme at the scale required for the demonstrator would be difficult. A substitute for the honeycomb resin reservoir would need to be identified and its suitability for this infusion validated via experiment. Implementation of the reservoir would also require modifications to the demonstrator tool, leading to additional project complexity and cost. The in-plane resin infusion scheme is therefore selected for the monolithic keel.

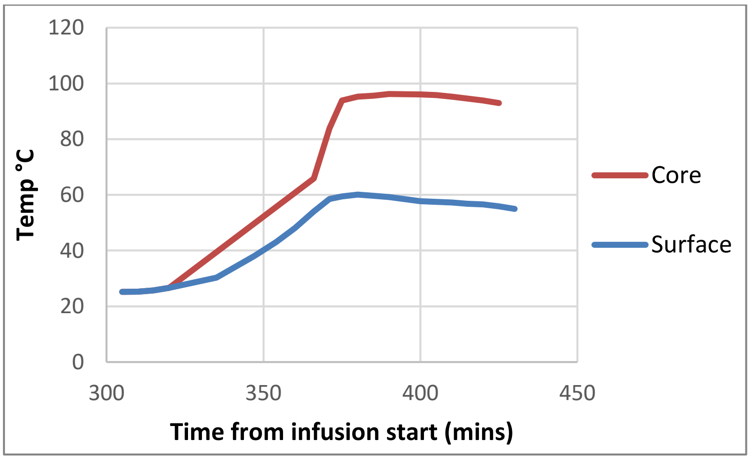


Figure 61: Monolithic block infusion exotherm measurement

4.6.3 Application of monolithic infusion scheme to a 75m hull shell

An in-plane infusion along the fibre direction (keel to gunwale) is identified as the most suitable monolithic infusion scheme. Whilst this scheme is applicable to the demonstrator manufacture, it should be noted that it is not representative of a 75m hull shell as it relies on the monolithic keel having an open face at the base of the hull. Figure 62A shows this issue. The surface inlet significantly reduces the risk of lock-offs in the core of the monolithic section by providing a uniform resin flow front. However, implementing this surface inlet in a symmetric hull shell would create a critical structural weakness along the keel. Modifying this setup to instead feature two linear inlets on the top and bottom of the laminate is possible, although this would significantly increase the risk of defects within the monolithic laminate (Figure 62B). This change was deemed too high-risk for the demonstrator production (considering the available time and resources) and is instead left for future work.

As previously discussed at the start of this chapter, the primary focus of this work is to produce a demonstrator of the hull shell. Infusion strategies that are not completely representative of a 75m hull shell are allowed provided they significantly reduce process risk.

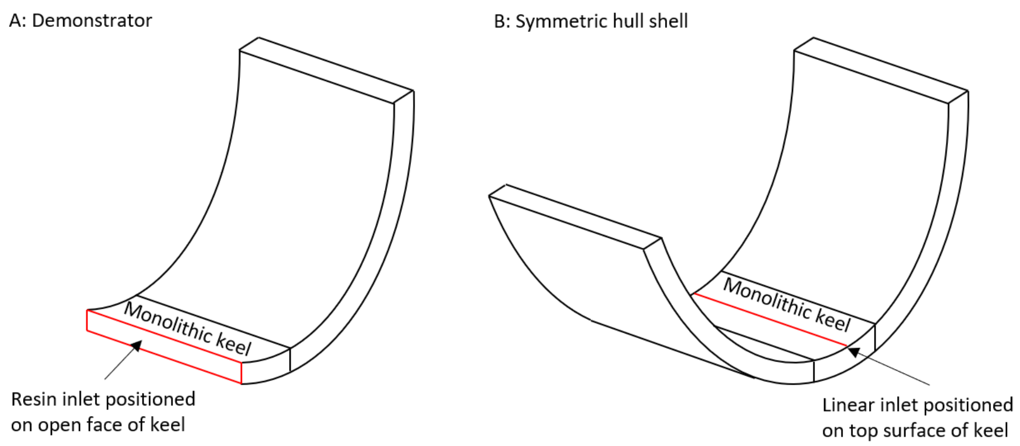


Figure 62: Monolithic keel resin inlet positions for (A) demonstrator and (B) symmetric hull shell

4.7 Voidage in large infusions

The formation of voidage within laminates is one of the greatest risks of an infusion process. The pressure differential between the preform and ambient environment during an infusion process can result in the surrounding air being drawn into the preform if there are small holes in the vacuum bag perimeter seal or over the vacuum bag surface. These air leaks can lead to voids forming within the resin which, depending on their size and distribution, may or may not be acceptable depending on the defect acceptance criteria for the specific project. The defect acceptance criteria for this case study states an acceptable maximum bubble diameter of 3mm. A defect area may contain no more than 2 bubbles within 5 inches, and no defect areas can be located within 1 inch of each other. Suitable process design is therefore required to maximise vacuum bag integrity, especially for larger infusions such as the selected case study where the greater vacuum bag area and limited tool surface accessibility will increase the chance of leaks.

Dissolved gasses may also be extracted from resin systems under low pressures and form bubbles. (Oosterom, S., et al., 2020) demonstrated how resin that is oversaturated with oxygen can result in voidage levels of 1% to 2% across a laminate, whilst undersaturated resin results in voidage levels of less than 0.2%. Degassing is a technique used in the composites manufacturing industry to remove these dissolved gasses from the resin prior to infusion, thus reducing void content in the produced laminate (Afendi, et al., 2004). Degassing processes typically feature a vacuum chamber in which resin is exposed to low static pressures for extended periods of time.

The issue of voidage has been encountered within larger infusions at Airborne UK. Figure 63 shows the significant level of voidage observed within a thick monolithic laminate, which was produced as part of a production trial at Airborne UK. These voids appear evenly distributed throughout the part and are approximately 1-5mm in size. At the time of conducting this study the cause of this issue was not known. From the discussions above, it appears to be either due to a processing issue or related to material selection. There is a risk that this issue could also affect the ship hull demonstrator infusion (this voidage level exceeds the acceptance criteria of this project), so an investigation was conducted by the author to understand this voidage issue. This study was conducted early in the project and before the selected materials were available for testing. As a result, the materials that were used within Airborne UK's large commercial infusions were used instead. These are Prime 27 resin with extra slow hardener, Saerflow flow media and Saertex quadaxial glass reinforcement. The Prime 27 resin is always de-gassed (placed in a vacuum chamber to remove dissolved gases) prior to use.

Figure 63: Evenly dispersed voidage within a large cured composite section

Three potential sources of this voidage issue were identified based upon prior production experience and the discussions presented above. These are: resin inlet configuration, vacuum bag leaks and dissolved gasses within the resin. A series of investigations were conducted to investigate these areas and improve the infusion setup to reduce the level of voidage.

4.7.1 Resin inlet configuration

For infusions conducted using a static resin reservoir such as a bucket, it is possible that a small volume of air can become trapped in the resin feed tube between the clamp (a few centimetres from the part) and the resin bucket. This is because this region is not under vacuum during the infusion setup, as shown in Figure 64. When the clamp is released, this small volume of air is pulled through the part, normally ahead of the resin flow front. It is generally good practice to allow some time for this volume of air to be fully evacuated from the part before starting the infusion. To do this, one can open the inlet clamp periodically to bring

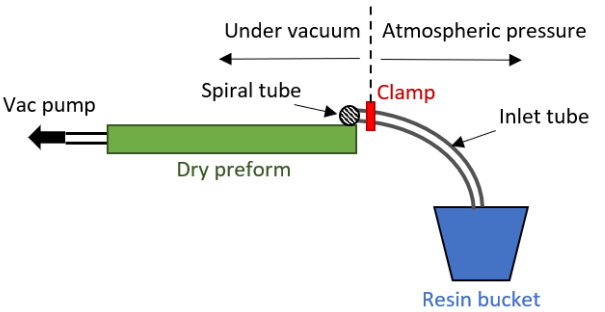


Figure 64: Atmospheric pressure in inlet tube creates a region of trapped air

the resin flow front slightly past the clamp, completely filling the inlet tube with resin without infusing the part. The resin is held at this position for a specified duration to allow any air to be drawn out through the vacuum outlet.

An investigation was conducted to determine the effect of this volume of air on the voidage level during the infusion of small, thin laminates. Three identical infusions (3-ply Saerflow, 0.2m wide, 1m long) were conducted, the only variation between them being the duration that the resin was held in the inlet tube prior to infusion (to allow air within the tube to evacuate out of the part). Figure 65 shows the inlet spiral tube for the three infusions. The durations that the resin was held in the inlet tube was 0, 5 and 60 minutes for infusions A, B and C respectively. Bubbles were visible in the inlet spiral for the 0 and 5 minute tests, whilst the 60-minute hold time appears to have prevented any bubbles forming at the inlet. However, the small quantity of bubbles seen in this test was not equivalent to the voidage issue previously defined.

This test also highlighted the importance of positioning the resin feed tube below the laminate as this prevents air collecting in the tube due to buoyancy forces. A resin feed with a steady inclination up towards the laminate is preferred. Figure 66 shows this effect.

Finally, the position of the spiral tube was also found to have an impact on how bubbles collected around the inlet. The initial flow front can sometimes contain bubbles within the resin due to the mixing of air and resin within the inlet feed tube. It is important that these bubbles remain within the flow front so that they can be evacuated from the part at the vacuum outlet. However, if the resin flow front does not move towards the outlet, these bubbles can become trapped in the part. Figure 67 highlights how positioning the spiral tube away from the edge of the preform can create a secondary flow front that traps air in the laminate. To prevent this, it is suggested that the spiral tube be positioned flush against the edge of the preform.

4.7.2 Vacuum bag leaks

Leaks can easily form across the infusion setup due to a broken tacky tape seal or vacuum bag punctures made during transport and handling. The voidage issue was more commonly observed around the resin inlet, which in the case of the larger infusions, was positioned next to the tacky tape seal. Breaks in the tacky tape seal may create localised leaks that feed air directly into the spiral inlet.

An investigation was conducted to understand if stray glass fibres on the tool surface, a common product of the layup procedure, could break the tacky tape seal and create air leaks within the infusion. The Saerflow material tends to shed small glass fibres during handling and layup.

Figure 65: Bubbles (highlighted in red) within inlet spiral tube depending on time that resin was held at clamp. A = 0 minutes, B = 5 minutes, C = 60 minutes.

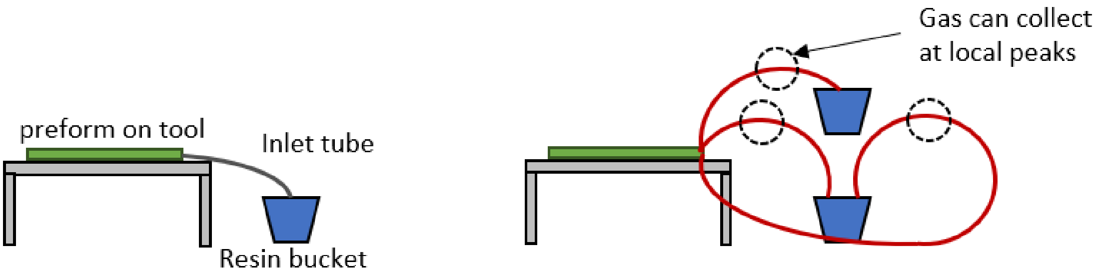


Figure 66: Resin feed tube positions. Left = preferred configuration

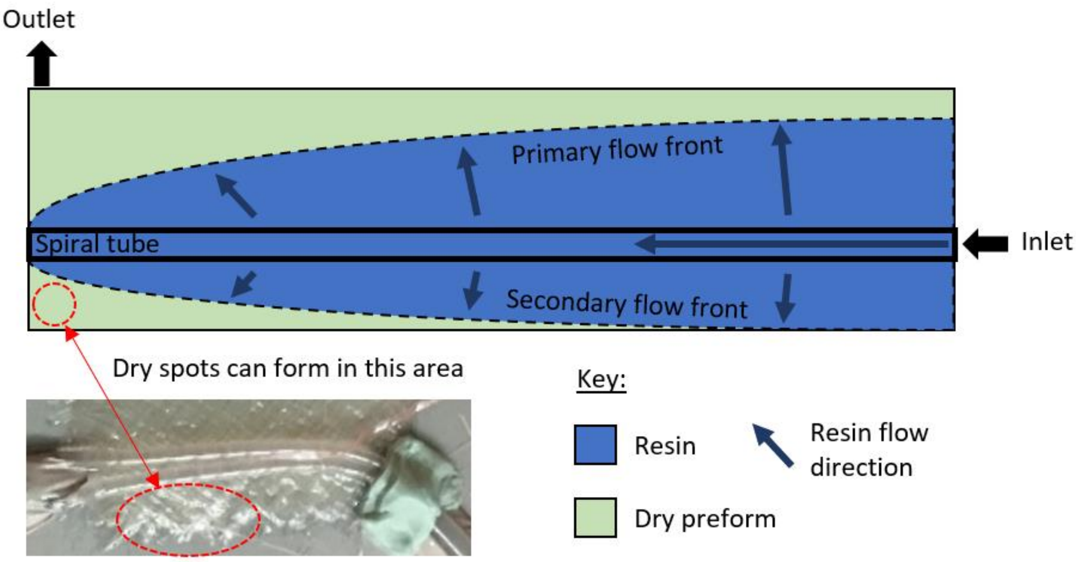


Figure 67: Spiral tube position increases the risk of dry regions forming

Two identical panels (3 plies Saerflow) were laid up and vacuum bagged on a tool surface with no intentional leaks. A vacuum level of -0.9 bar was applied for 2 hours, after which a 2-hour drop test was conducted that indicated no drop in vacuum level. Small fibres from the Saerflow material were then placed across the tacky tape seal next to the spiral tube inlet to simulate a leak (Figure 68). A bundle of fibres was used in panel A whilst a single fibre was used in panel B.

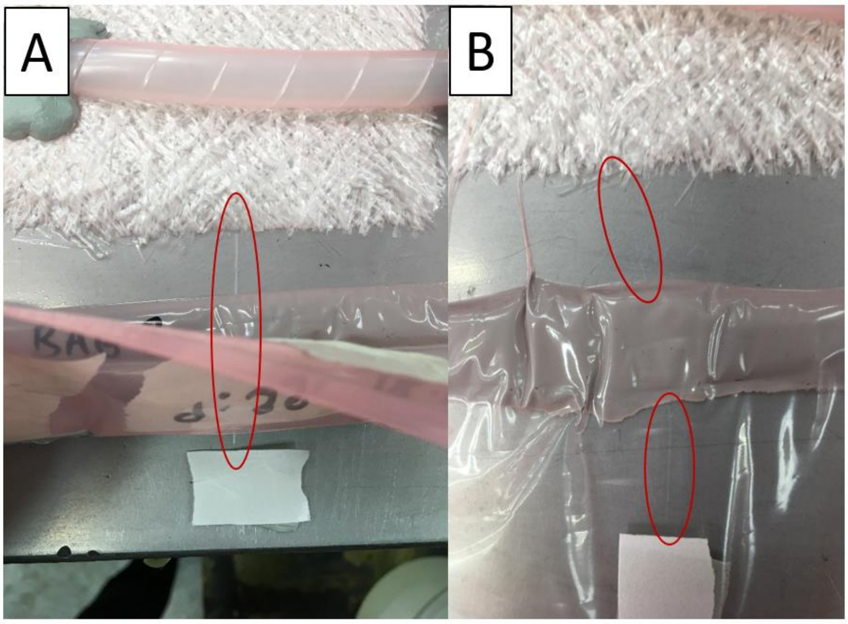


Figure 68: Fibre bundle (A) and single fibre (B) across tacky tape seal

Figure 69: Laminate infusions with a fibre bundle (A) and single fibre (B) crossing tacky tape seal

Both panels were then infused with the same batch of Prime 27 resin. Figure 69 shows the effect of these broken tacky tape seals on the infusion processes. The bundle of fibres (panel A) creates a noticeable leak that can be easily traced back to its source. The single fibre (panel B) does not create a noticeable leak. Neither result corresponds to the evenly distributed voidage issue seen in large infusions. However, this investigation highlights the significant effect a small bunch of fibres can have on an infusion. Considering Saerflow will be used in the demonstrator production, it is important that these stray fibres be removed before the vacuum bag is applied.

4.7.3 Dissolved gases within the resin

The resin is currently degassed in a large vacuum chamber prior to infusion. Despite this, it may possible that some gases remain within the resin which are later extracted under vacuum during the infusion process. If this is the case, then the current de-gassing procedures may be insufficient. Currently, 300 litres of prime 27 resin are held in a 500-litre vacuum chamber and exposed to -1 bar vacuum for 24 hours. The resin is then recirculated at -0.4 bar vacuum for 2 hours immediately before use. An injection machine is used to transfer the resin from the vacuum chamber into the preform. At no point in this process is the resin exposed to the ambient environment.

To investigate whether the current de-gassing procedure was sufficient, two 700g samples of Prime 27 resin were placed in a vacuum chamber and de-gassed. Sample A was taken from the injection machine after 300 litres of the resin had been de-gassed as described above. Sample B was taken from the same batch, but instead this 700g volume of resin was de-gassed in a smaller vacuum chamber for 20 minutes at -1 bar vacuum. Both samples appeared to contain no visible bubbles at ambient conditions. The samples were then placed in a vacuum chamber together and exposed to -1 bar vacuum. Figure 70 shows the bubbles that were extracted from the resin samples after 10 minutes.

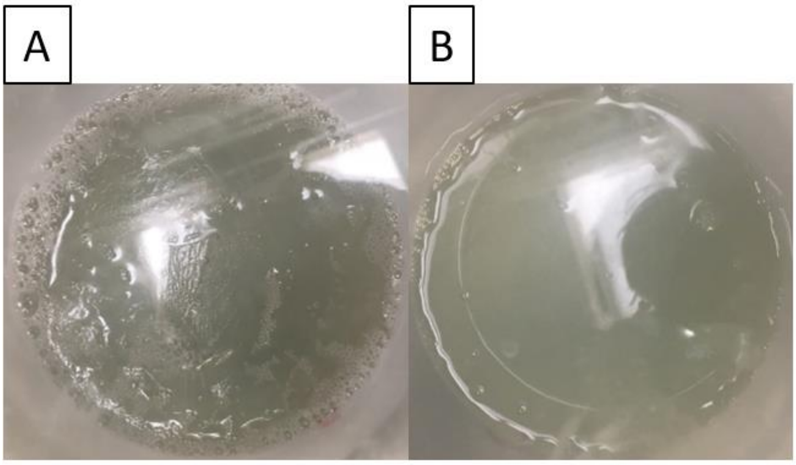


Figure 70: Resin samples under vacuum. A: directly from injection machine, B: from injection machine and de-gassed prior to test.

A significant amount of bubbles formed in sample B during the test. These bubbles appear to be similar in size and number to those seen in the cured laminate in Figure 63, indicating that insufficient degassing could be the primary cause of this voidage. Sample A demonstrates that it is possible to remove the majority of these bubbles through an alternative degassing procedure.

This investigation indicates that the current degassing procedure for large volumes of resin is insufficient, hence why this voidage issue is predominantly seen in larger infusions. Further work is therefore required to modify the degassing procedure.

4.7.4 Alternative degassing procedure

Degassing small volumes in a vacuum chamber was demonstrated to be effective at removing bubbles within the resin (sample B, Figure 70), however this is not practical for large commercial infusions due to the time and resources required. A commercially viable and effective degassing procedure must therefore be identified. Four alternative degassing procedures were developed and tested with Prime 27 resin. Each process is described below and evaluated against several criteria.

4.7.4.1 Process 1: Degassing through Scotch-Brite

Scotch-Brite is a type of scouring pad made from finely meshed nylon fibres. Its primary use is for cleaning, scouring, and sanding of household and industrial items, however it has also been used in the composites industry to help with degassing resin due to its fine mesh structure. Pieces of Scotch-Brite are sometimes added to buckets of resin before degassing to help extract gasses from resins. To avoid contaminating the resin, all Scotch-Brite is cleaned with acetone and air dried prior to use.

The first degassing process proposed in this study attempts to replicate the bubbling effect observed when infusing through glass fibre preforms. To do this, unmixed resin is drawn through Scotch-Brite under vacuum to separate the resin and dissolved gasses. The bubbly resin in then deposited in vacuum chamber and held under -1 bar vacuum for 1 hour to remove any remaining bubbles. A vacuum bag and a series of infusion tubes are used to “infuse” the resin through the Scotch-Brite. Figure 71 shows this process and its effectiveness at extracting gasses from the resin (compare A and B in Figure 71).

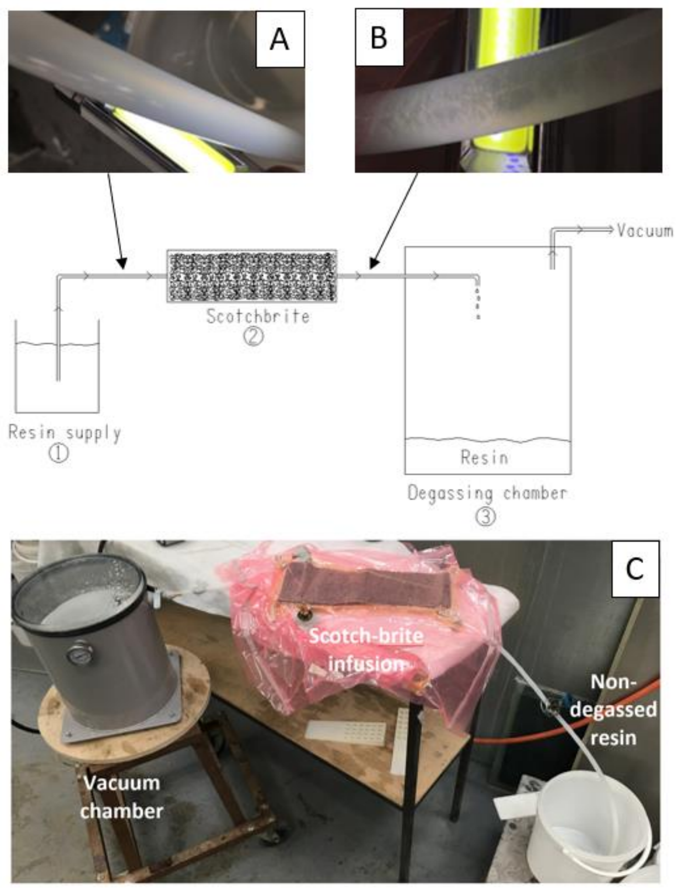


Figure 71: Degassing concept 1. A and B show the inlet and outlet tubes. C shows the practical setup. 1, 2 and 3 indicate the sequence of events.

4.7.4.2 Process 2: Dripping resin through Scotch-Brite

This concept attempts to simplify process 1 by removing the intermediate infusion step. Instead, resin is fed directly into a degassing chamber and drip fed through a porous vessel containing Scotch-Brite. The resin then moves through the Scotch-Brite via gravity and collects in the base of the chamber. The entire chamber is exposed to -1 bar during this process.

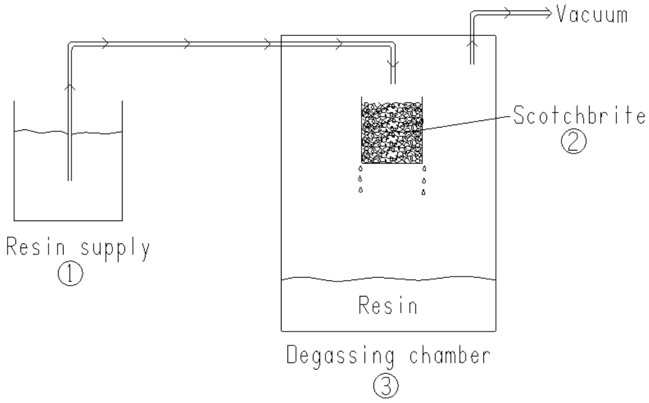


Figure 72: Degassing concept 2: 1, 2 and 3 indicate the sequence of events.

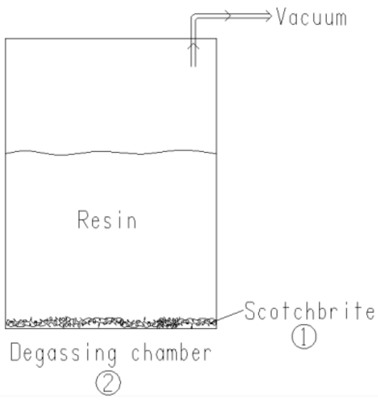


Figure 73: Degassing concept 3: 1 and 2 indicate the sequence of events.

4.7.4.3 Process 3: Degassing resin with Scotch-Brite at base

This modification aims to simplify the process further by simply placing a layer of Scotch-Brite at the bottom of the degassing chamber. This is the "conventional" method that is sometimes used in industry. The addition of the Scotch-Brite is seen to improve the degassing process compared to a static chamber of resin. However, the Scotch-Brite is only in direct contact with the resin at the base of the chamber, so its effectiveness is limited for larger volumes of resin.

4.7.4.4 Process 4: Air sparging

In this scheme resin is held under vacuum within the degassing chamber. A valve at the base of the chamber is opened to allow air to bubble up through the resin and out the vacuum line. As the bubbles move through the resin, they extract dissolved gasses, slowly growing in size as they move through the resin. A filter is used disperse the airflow evenly throughout the resin. After the resin has been subjected to this process for 2 hours, the valve is closed, and the resin is left under vacuum for a further 1 hour to remove any remaining bubbles in the resin.

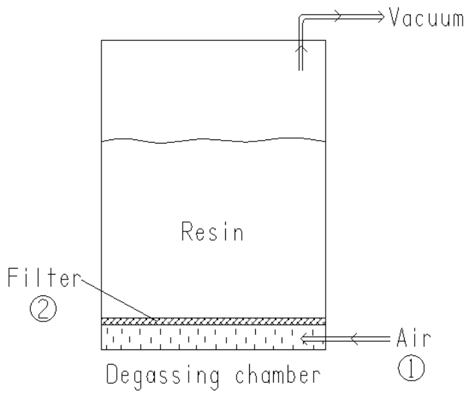


Figure 74: Degassing concept 4: 1, and 2 indicate the sequence of events.

4.7.4.5 Comparison and evaluation of procedures

Each concept was used to de-gas 5 litres of Prime 27 resin and then evaluated against six criteria:

- **Degassing effectiveness:** A visual inspection of how many bubbles are formed (number and size) in a 400g sample of the de-gassed resin when placed in a vacuum chamber for 5 minutes. Visual inspection of bubbles is made in reference to the acceptance criteria outlined in Table 2 (Maximum bubble diameter of 3mm, a defect area may contain no more than 2 bubbles within 5 inches, and no defect areas can be located within 1 inch of each other). This is only used as a guide, as it is difficult to relate surface bubbles in liquid resin to voidage within a cured laminate.
- **Speed:** Time to convert non-degassed resin into degassed resin. This is important as the degassing procedure will be used within a production line, and therefore cannot limit production rates.
- **Setup complexity:** The time and training required to setup the degassing system. Any additional hours spent on the degassing procedure can further increase costs and limit production rates.
- **Maintenance:** The frequency at which maintenance/cleaning/replacing materials must be conducted. This translates to labour costs and process down-time.
- **Process robustness:** How susceptible each concept is to a factory environment (knocks/damage) and operation by different users.
- **Material cost:** The cost of any additional recurring and non-recurring materials, excluding labour costs previously mentioned.

4.7.4.6 Selection of degassing procedure and future work

Table 32 presents the evaluation of the four concepts against the defined criteria and indicates that concept 5 is the most suitable degassing procedure for large volumes of resin. A similar degassing procedure is also described in literature (Afendi, et al., 2004). This concept was therefore selected for use in large scale infusions. The effectiveness of this concept compared to the current degassing procedure was demonstrated by infusing two identical large laminates.

In this test two laminates consisting of 3 plies of Saerflow, 0.3m long by 2.5m wide were infused with Prime 27 resin with extra slow hardener. Test A featured resin degassed using the current procedure, whilst test B implemented concept 5 instead. A wide laminate was selected for this final text to maximise the size of the inlet and thus the voidage effect. The 2.5m wide inlet was also representative of the larger commercial infusions at Airborne UK. Figure 75 shows the setup for this final test.

Figure 75: Wide infusion trial setup

Table 32: Evaluation of various degassing procedures.

Evaluation criteria *(weighting)*	Concepts			
	1 (Infused)	3 (Dripped)	4 (Static)	5 (Air sparging)
Degassing effectiveness *(1)* *(resin is degassed and then placed in a vacuum chamber)*	No bubbles formed in the degassed resin sample after 5 mins under vacuum.	Some 1-2mm bubbles formed in the resin sample after 5 minutes under vacuum.	Multiple 1-2mm sized bubbles formed in the resin sample after 5 minutes under vacuum.	No bubbles formed within the degassed resin sample after 5 mins under vacuum.
Speed *(1)*	70 minutes cycle time to process 5 litres.	110 minutes cycle time to process 5 litres of resin.	6 hours to remove visible bubbles/froth from 5 litres of resin	170 minutes cycle time to process 5 litres of resin.
Setup complexity *(1)*	High complexity due to bagging setup; 16 Scotch-Brite pads must be cleaned and dried, then aligned accurately with inlet and outlet tubes under vacuum bag. Entire process takes 1 day (due to Scotch-Brite prep)	The porous bucket that holds the Scotch-Brite must be created. The Scotch-Brite must be cleaned and dried, and then cut to accurately fit the internal dimensions of the bucket. This process is time consuming.	Scotch-Brite must be cleaned and dried. Otherwise, the system is fairly simple to setup.	Intricate air dispersion system must be setup at the base of the chamber to evenly distribute bubbles throughout the resin.
Maintenance *(1)*	Scotch-Brite pads wear down due to resin exposure. It has been determined through trials that the Scotch-Brite pads should be replaced every 100 hours of use. This means the degassing system must be remade every 100 hours.	Scotch-Brite should be replaced after 100 hours of use. Entire process must be setup again.	Scotch-Brite should be replaced after 100 hours of use. Entire process must be setup again.	No significant planned maintenance is required.
Process robustness *(1)*	Potential for vacuum bag leaks, especially as this is a semi-re-useable setup.	Sealed vacuum chamber, so fairly robust. Some resin may flow over bucket if flow rate is too high.	Sealed vacuum chamber and no moving parts. Very robust.	Sealed vacuum chamber with no moving parts. Only minor issue is ensuring air inlet valve is opened to the correct level.
Cost *(1)*	This is the most expensive concept due to the amount consumable materials required. 16 pads of Scotch-Brite used in total. Negligible operational cost.	Less Scotch-Brite is used compared to concept 1. 8 pads of Scotch-Brite used in total. Negligible operational cost.	Less Scotch-Brite is used compared to concept 1. 8 pads of Scotch-Brite used in total. Negligible operational cost.	No consumable materials apart from the initial setup cost of the air dispersion system, which is low (series of infusion tubes under a porous surface). Negligible operational cost.
Total Score	**10**	**10**	**10**	**15**

Each infusion was closely monitored to observe any bubbles forming within the laminates during the process. Figure 76 shows a comparison of the two laminates immediately after infusion. Numerous bubbles of 1-2mm diameter can be seen within the laminate in infusion A. Whilst these bubbles are smaller than the maximum diameter defined in the acceptance criteria (3mm), the frequency and concentration of these bubbles far exceeds the acceptable limit (a defect area may contain no more than 2 bubbles within 5 inches, and no defect areas can be located within 1 inch of each other). The quality of laminate A is therefore deemed unacceptable. No bubbles can be seen in Laminate B, indicating that the alternative degassing procedure successfully reduced voidage levels and produce a laminate of sufficient quality to meet the project requirements.

This degassing procedure is therefore selected as the most suitable approach to addressing the voidage issue within large infusions. This degassing approach implemented into the production line of large-scale infusions at Airborne UK and would be available for the hull shell demonstrator manufacture if required. However, after this study was conducted the author repeated these tests with the Albidur resin, and no voidage was seen, with or without degassing, indicating that this voidage issue is less of a concern for the hull shell case study. The degassing procedure identified in this study was therefore deemed unnecessary for the demonstrator production. However, if similar levels of voidage were to occur during the demonstrator production in the absence of vacuum bag leaks, then this degassing procedure could be applied if necessary.

Figure 76: Bubbles within laminates immediately after infusion. A: Current degassing procedure, B: New degassing procedure (concept 5).

4.8 Representative infusion trial

The section describes a final infusion trial that was conducted to test the proposed infusion scheme. A full-scale representative section of the demonstrator preform was created and infused in this investigation to identify any potential issues with the strategy prior to production of the demonstrator. This preform was 460mm wide and constructed according to the demonstrator design. This is a critical step in the project as there are only enough materials to manufacture one demonstrator. This investigation was also used to refine all other elements of the manufacturing process, including tool preparation, preform layup, vacuum bagging, infusion, cure, and demoulding. This section only discusses the infusion process, and details of the other manufacturing steps are provided for the demonstrator manufacture process in chapter 5.

> **Question:** Can the proposed infusion schemes for individual regions of the part be combined to successfully produce a full-scale representative section?
>
> **Data acquisition method:** Experiment.

4.8.1 Proposed infusion scheme

The infusion strategies for thick vertical sandwich panels and monolithic laminates that have been developed in this chapter are combined to present a complete infusion strategy for the full-scale demonstrator. Figure 77 outlines the final infusion strategy. This diagram is based on the revised design presented in Figure 29, Chapter 3.

The demonstrator is infused in the in-plane direction from the keel to the gunwale using a vacuum bag over a female steel tool. Regular resin inlets are positioned on average every 1m, although exact positions vary depending on local structural details. Where appropriate, inlets are located at structural transitions to minimise the negative effects of potentially complex resin flows. For example, two sets of inlets are positioned either side of the joint 1 monolithic insert to ensure good wet-out at the interface between monolithic and sandwich panel.

The monolithic keel is infused first with a large resin inlet positioned on the open face. This creates a uniform resin flow front throughout the width and thickness of the part that progressively moves upwards towards the gunwale. The sandwich panels are infused with parallel linear inlets feeding resin to the inner and outer laminate skins. These inlets are positioned regularly every metre along the circumference of the part to maintain a reasonable infusion rate. The first of these inlets is located at the keel/SP1 interface, where the sandwich panel begins. Spiral tube is placed over the inner laminate to form the inner inlets, whilst open channels are machined into the foam core to create the outer laminate inlets. The inlets are opened once the resin flow front has passed their position by approximately 100mm to reduce the chance of lock-offs forming in these areas. A single linear vacuum outlet is positioned along the gunwale.

An injection machine shall be used to mix and deliver the resin into the part. The injection machine utilises pumps which can be used to provide a positive or negative pressure change. A positive pressure change can be applied to counter the hydrostatic pressures higher up the part. This should allow the resin infusion to maintain a steady speed throughout the process, independent of height. This should also limit the cured laminate thickness variation with height.

A network of infusion channels and through-thickness perforations are machined into the foam core sheets to aid resin flow throughout the preform. These features allow for unrestricted resin flow throughout the cross section, improving resin wet-out and reducing the risk of dry areas forming. Single plies of Saerflow flow media are placed between the foam core sheets to ensure good bonding between them, and thus producing a continuous foam core section without discontinuities. Saerflow flow media plies are also located within all structural laminates at a rate of 1 for every 10 quadaxial reinforcement plies. These Saerflow plies increase the average laminate permeability and improve resin flow through the preform.

Table 33 outlines the key measurable/controllable inputs and outputs for this infusion process. These were identified using expert knowledge, prior experience, and review of relevant literature (Potter, K., 2014) and the IPO Model (Figure 19, Section 3.6). Process input variables such as resin viscosity and reinforcement permeability are not included as these are not directly controlled or measured. Only the process output variables that are directly relevant to the project requirements are considered.

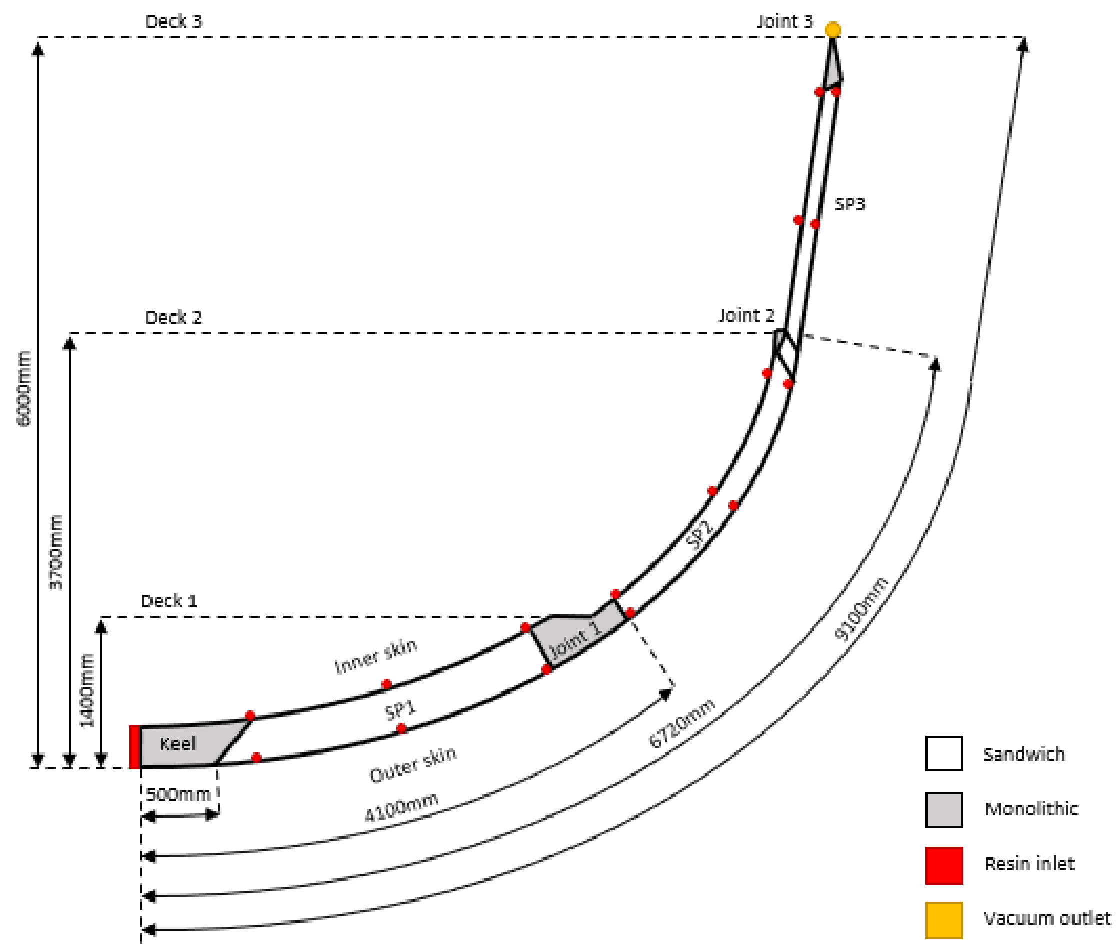


Figure 77: Demonstrator infusion strategy

4.8.2 Infusion setup

This section briefly outlines the approach taken to prepare the tool and preform for infusion, and any important lessons learned during this process that can be applied to the demonstrator. As this chapter primarily focuses on the infusion process, further details of other process stages (such as tool preparation, layup methodology, cure, and demoulding) are presented in Chapter 5. Unless otherwise stated, the manufacture of this final infusion trial follows the methodology presented in Chapter 5. The author conducted all stages of this manufacturing trial with the help of Airborne UK production staff. This allowed the author to gain a first-hand understanding of the strengths and limitations of the manufacturing process and the suitability of the previously defined tolerances and acceptance criteria. This information was used to identify potential improvements to the process prior to the demonstrator manufacture.

Table 33: Key infusion process inputs and outputs

Name	Classification	Description
Tool preparation quality	Input	Cleaning of the tool surface and correct application of mould release is a critical step in ensuring a good quality of the external hull surface.
Ambient temperature	Input	Temperature variations can affect resin viscosity and gel time. Temperature must lie within defined acceptable range throughout infusion.
Relative humidity	Input	High levels of humidity can affect part quality. Humidity must lie within defined acceptable range throughout infusion.
Resin mix ratio	Input	Mix ratio determines gel time. Mix ratio should be selected to provide suitable gel time for predicted infusion duration.
Vacuum bag integrity	Input	Ability of vacuum bag to hold vacuum. Small leaks in the bag may reduce applied vacuum level and increase number of defects such as dry spots and voidage.
Applied vacuum level	Input	Applied vacuum level at the vacuum outlet(s). The maximum vacuum level that is achievable may vary based upon the equipment used and total load on the equipment (i.e., other large infusions being conducted in the factory using the same vacuum line/pump).
Applied injection pressure	Input	The injection machine can provide positive pressure at the mixing nozzle to counter hydrostatic pressures encountered during the vertical infusion. This variable can be manually controlled throughout the infusion.
Part quality/ level of defects	Output	Visual inspection is used to detect any defects within the part (after cure). Acceptable defects are outlined in Table 2. Ply positioning tolerances are defined in Table 24.
Geometric accuracy of part	Output	Evaluation of the part surface geometry and sectional thickness compared to the design schematic. Geometry must meet the requirements outlined in Table 24.
Laminate fibre weight fraction	Output	Laminate fibre weight fraction is calculated based upon cured laminate thicknesses (see Section 4.2.1).
Total infusion duration	Output	Time from the moment the resin first enters the preform to the moment the preform is fully wet-out (Determined via observation and expert opinion/experience).

The tool was thoroughly cleaned and 5 coats of “Marbo FF 321/1 COD 64” release agent were applied to the entire tool surface (See Appendix A.2 for details of release agent selection). Plies of reinforcement were raised into positioned on the tool surface using a custom-made material deposition tool (see Section 5.4.3). Plies were then accurately positioned and laid up by hand. Plies could be positioned within +/-10mm both in the lateral and longitudinal directions (within the +/-10mm lateral and +/30mm longitudinal positioning tolerances). Plies that extended the full height of the demonstrator were clamped over the top of the tool. This approach combined with the adhesive backing on every ply restricted any noticeable downwards movement of plies. The use of the edge of the tool surface as a layup datum proved an effective approach for controlling ply lateral position (and hence ply orientation) within the acceptable tolerance. It was possible to handle and position the 400mm wide plies comfortably as the ply width lies well within the arm-span of a laminator. This trial did not feature any ply splice joints (because the preform was comprised of single, 400mm wide plies) making this layup procedure far simpler than the demonstrator layup procedure detailed in Chapter 5.

The infusion was setup according to the schematic in Figure 77. Figure 78 shows the vacuum bagged preform and inlet/outlet configuration. Two vacuum bags were applied to reduce risk of leaks and for additional vacuum compaction post-infusion (See Chapter 5 for further information). The part was held under vacuum overnight prior to infusion.

Figure 78: Preform under vacuum

The infusion strategy in Figure 77 is based upon the final design featured in Section 3.8.6, which was the product of several design iterations within the RAMSSES WP17 consortium. These iterations were ongoing throughout the infusion process development and had not concluded at the time of conducting this final infusion trial. As a result, this final infusion trial features some details which are not representative of the final demonstrator. These are outlined below:

- The pre-cured monolithic region at joint 1 was omitted from this test. Foam core was used in its place.
- A sharp 90° transition was implemented at joint 2 rather than the combination of a gradual transition and a monolithic "step preform" that is proposed in Section 3.8.6.

These two changes are not thought to significantly influence the infusion process, meaning this trial is still mostly representative of the demonstrator infusion procedure. The remainder of the preform in this infusion trial was constructed in accordance with the final design (Section 3.8.6). Because of these differences, details of the joint manufacture are omitted from this section and are instead discussed in further detail in Chapter 5.

4.8.3 Infusion process

The infusion was conducted with Albidur 3.2 VE Hull resin (Mix 3, Table 10) using a Ciject Two Injection machine. The total duration of the infusion process was 350 minutes (approximately 6 hours), well within the 8-hour goal. Figure 79 shows the flow front progression with time on all three visible sides of the preform during the infusion process. Despite variations in sectional thickness and construction (monolithic vs sandwich), the resin flow rate remained consistent throughout the process. On average it took 40 minutes to infuse each 1m section of the preform, aligning with the results of the previous infusion trials. As with the previous vertical sandwich infusion trial, the resin flowed slightly faster along the sides of this preform in comparison to the inner skin. However, this difference in flow speed was minimal and was only noticeable at the vertical regions at the top of the preform. Figure 79 also displays the total injected resin volume, which varies depending on the sectional laminate area to provide a constant flow speed through the preform. The inlet positions and the times at which each one was opened and closed is also displayed in Figure 79. This data shows that all inlets were opened after the flow front had passed their position.

Figure 80 displays the variation in ambient temperature and relative humidity within the factory during the infusion process. A maximum temperature and humidity variation of 3^{o}C and 6% was observed, respectively. These changes did not appear to have any significant effects on the infusion process.

Figure 81 displays the applied injection pressure as measured from the injection machine console. Interestingly, positive injections pressures were not required to maintain a constant flow speed until the resin had reached the final two stages of the infusion. It is believed that the open channels within the foam core aided the resin flow to such an extent that the effects of hydrostatic pressures were reduced. A positive injection pressure of 0.3 bar was applied towards the end of the infusion to prevent deceleration of the resin flow due to gravity.

The flow front progression data in Figure 79 presents a similar trend to the flow front data measured during the 6m thin vertical infusion trial (Figure 44). Both sets of data show an approximate 40-minute infusion time for a 1 metre section. The similarities between the thin laminate and thick sandwich infusions indicate that the infusion strategy conducted in this final trial successfully addressed the challenges associated with thick sandwich infusions, allowing the resin to flow through the preform as if it were a thin laminate.

The resin infusion process appeared to have been a success with no visible infusion defects or dry regions observed in the part. Figure 82 shows the completed infusion and Figure 83 shows different areas of the infused preform. The structure was left to cure under vacuum and later demoulded from the tool, after which a large dry area was visible at the top of the part. Figure 84 shows this dry region (approximately 1m in length), which was not seen during the infusion process. This dry region formed overnight whilst the resin was left to cure in a liquid state. During this time, it is believed that the resin had drained downwards through the preform to create a dry region at the top. To prevent this happening in the demonstrator production, it is suggested that the resin cure time be matched closer to the infusion duration, so that cure occurs soon after the infusion is complete. This should minimise the time in which the resin can drain downwards.

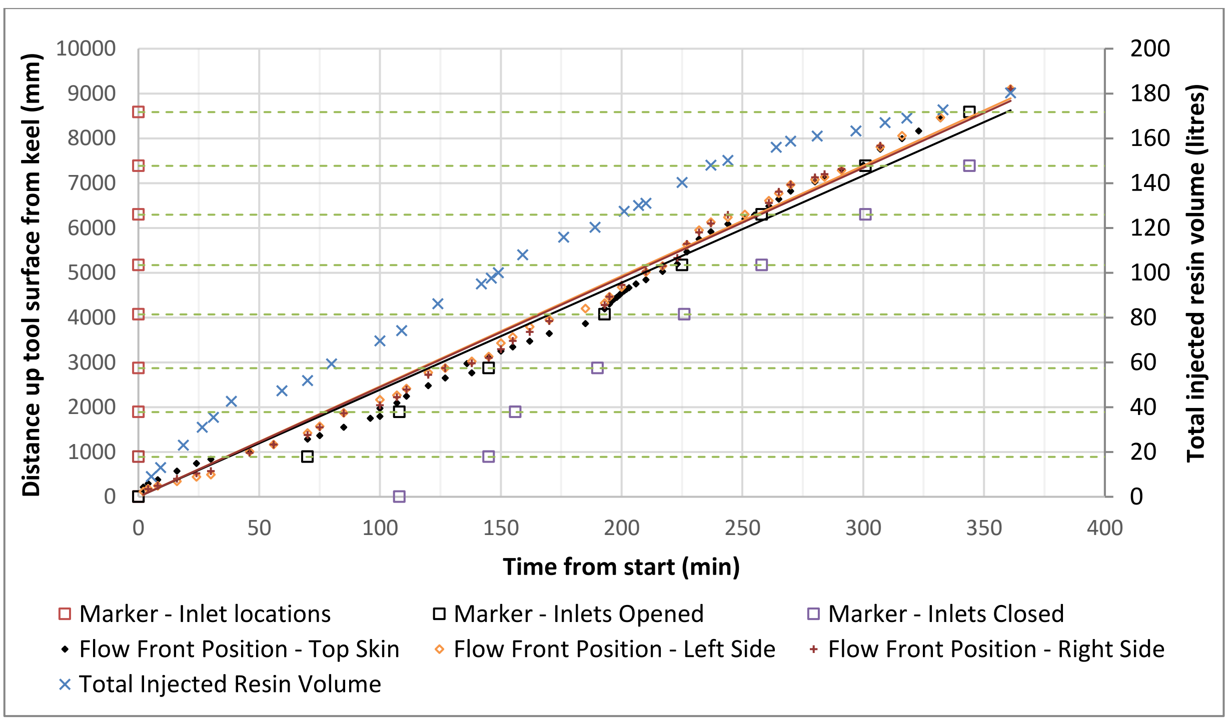


Figure 79: Flow front progression, resin injection rate and opening of inlets vs time

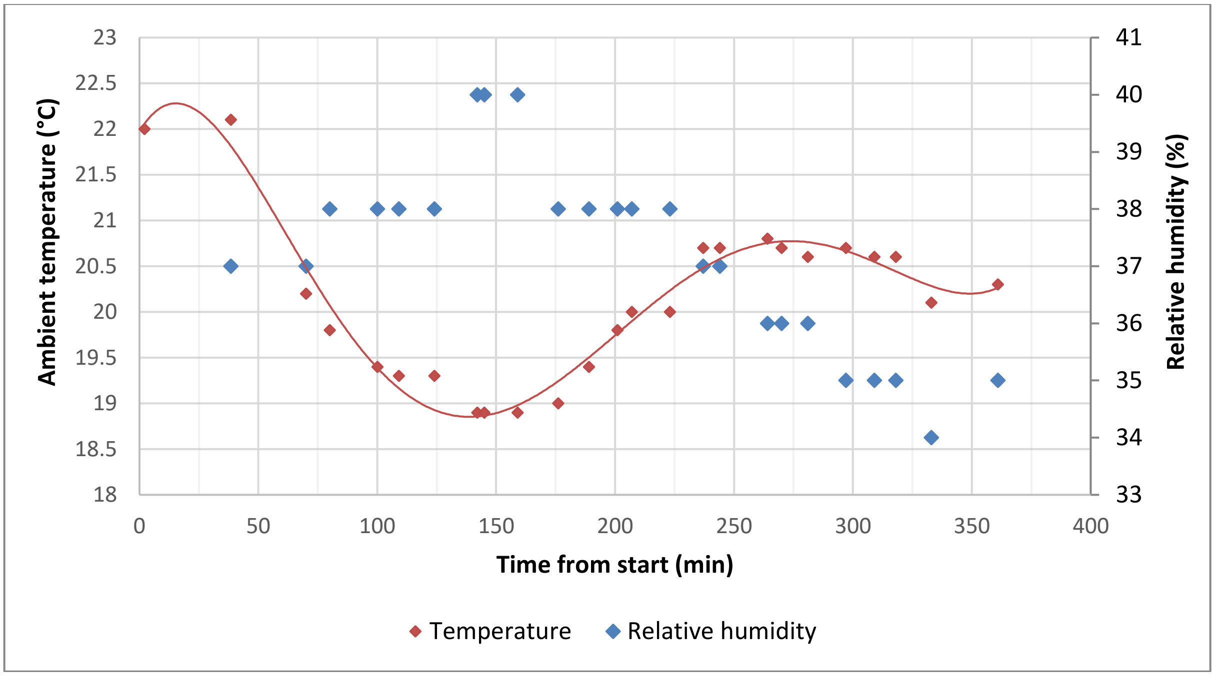


Figure 80: Ambient temperature and relative humidity variation with time

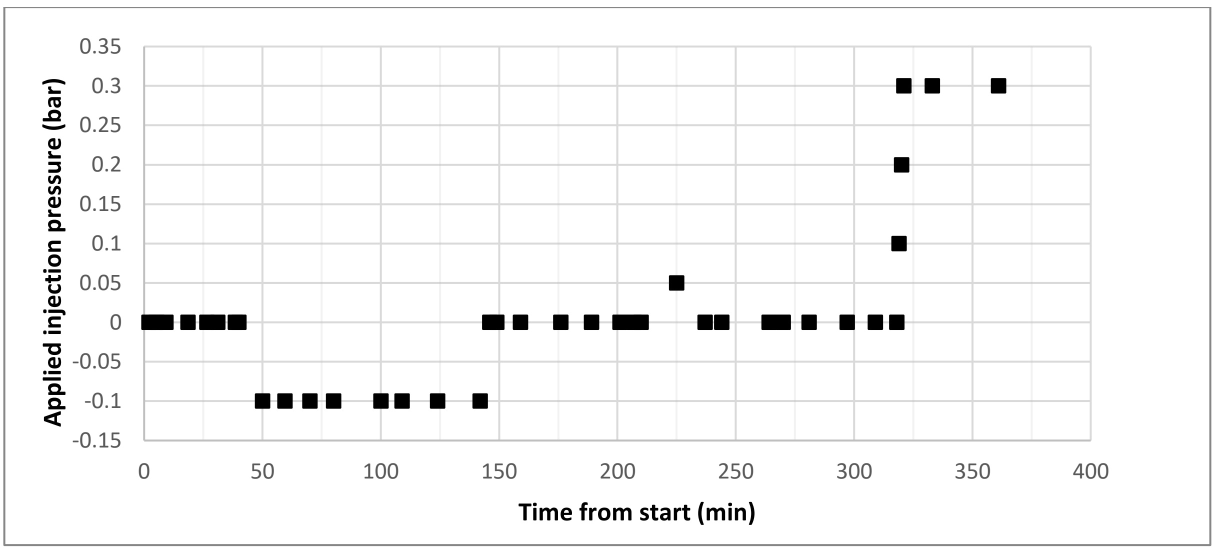


Figure 81: Injection pressure applied by the injection machine

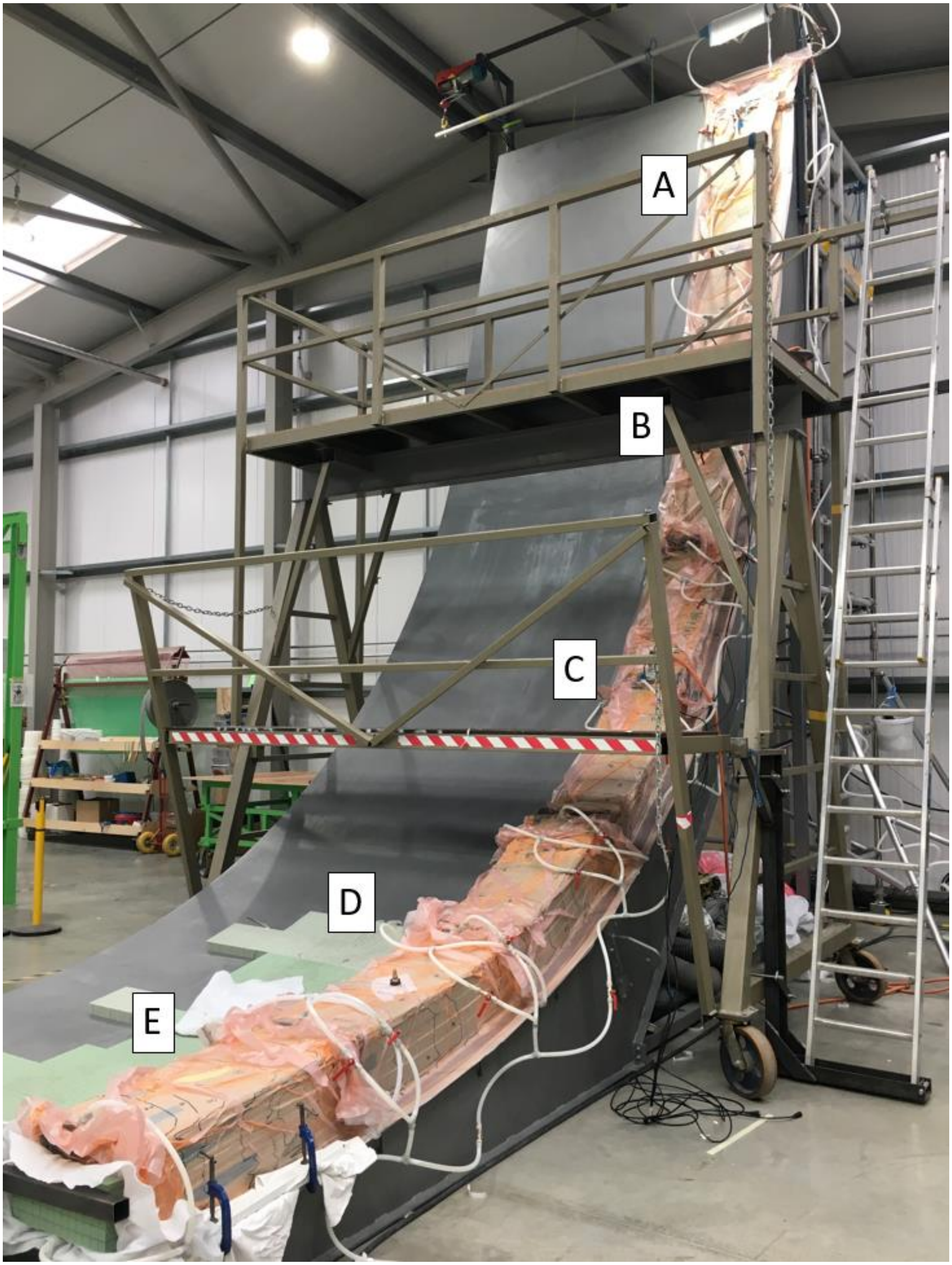


Figure 82: Completed final infusion trial

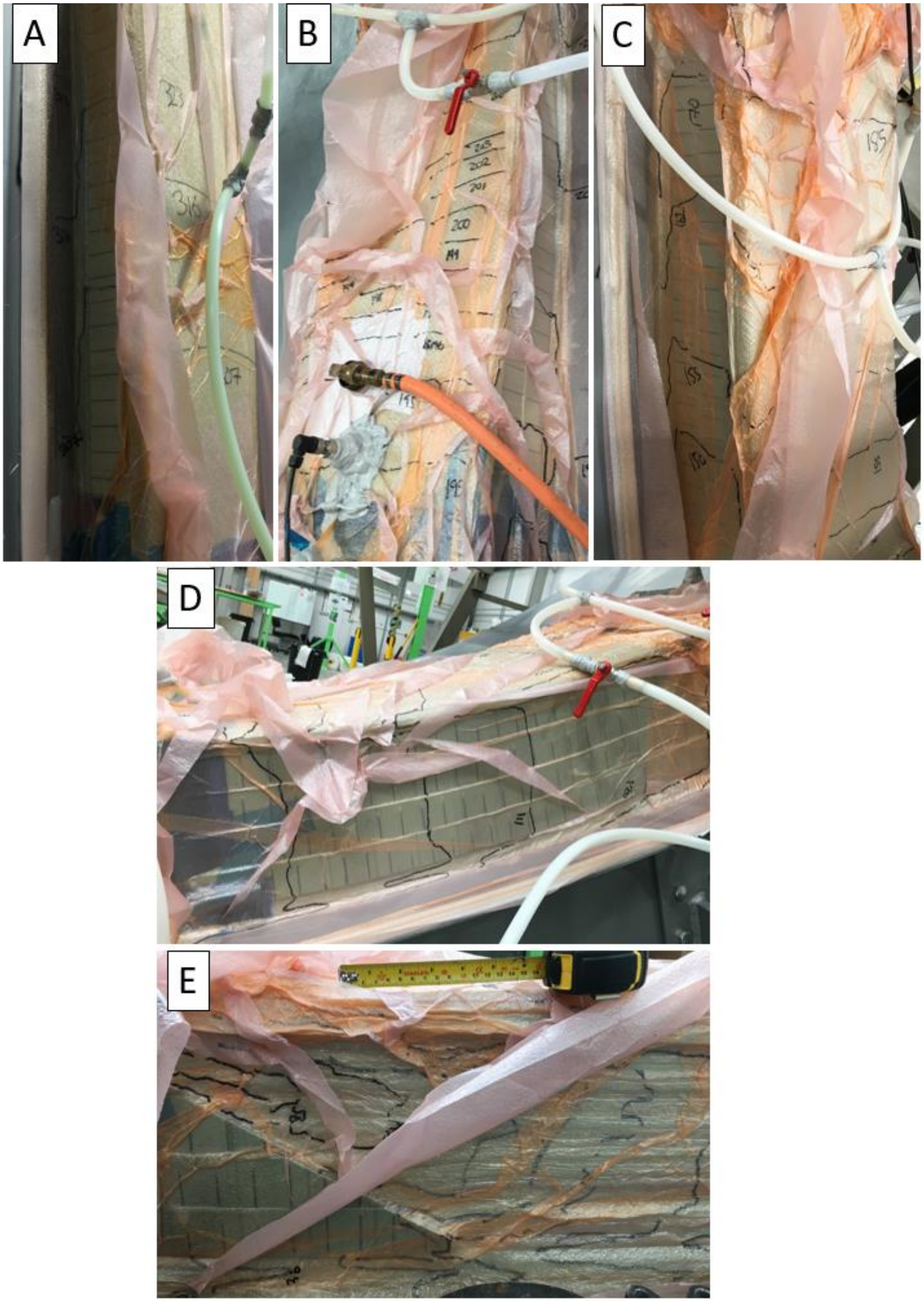


Figure 83: Close-up of completed final infusion trial (Letters correspond to locations in Figure 82)

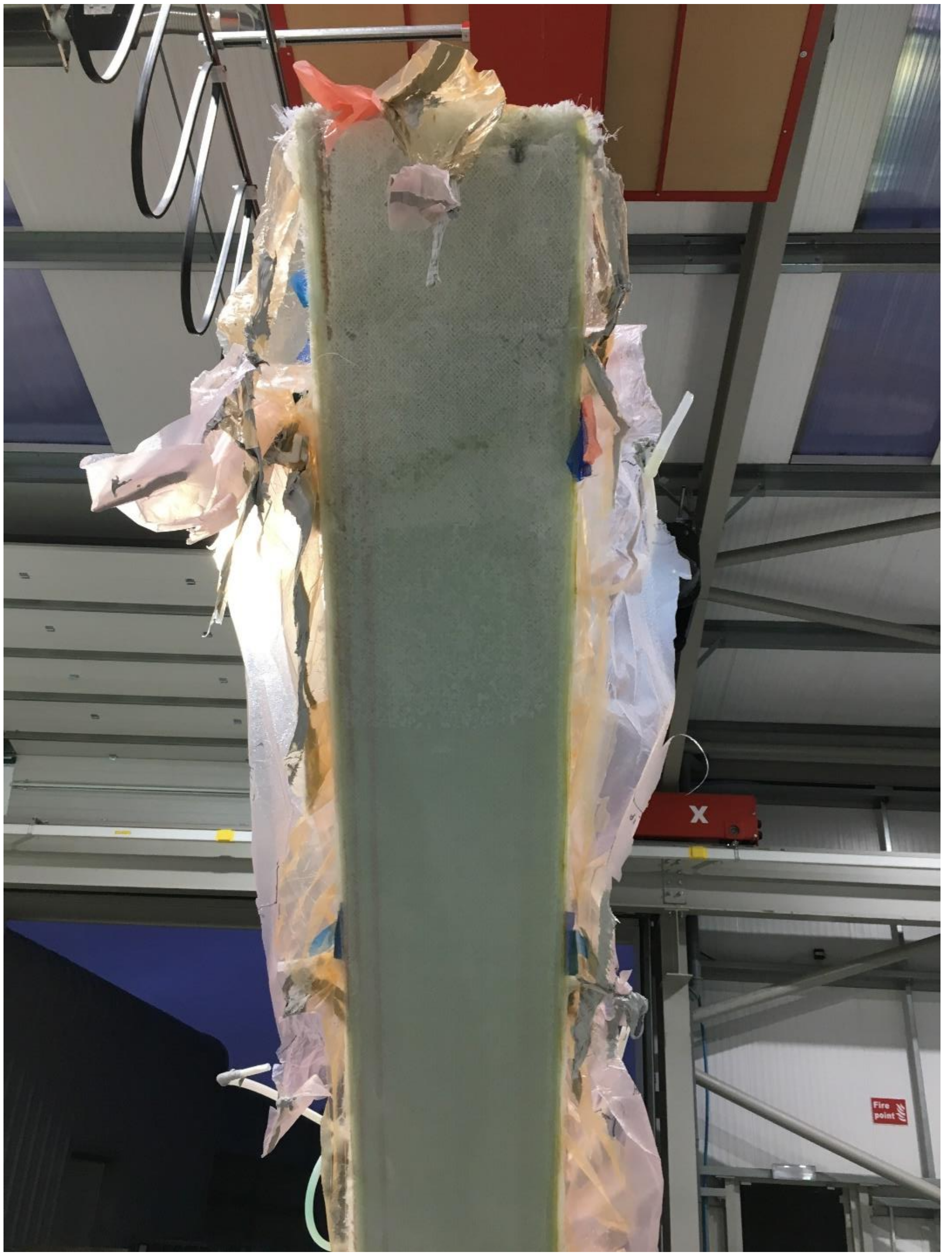


Figure 84: Dry region at the top of the cured part (final infusion trial)

4.8.4 Part inspection

The part was inspected after demoulding. Overall, the laminate appeared to be of good quality, meeting the acceptance criteria outlined in Section 3.2.1. Average laminate fibre weight fraction was calculated as 67.7%, which lies within the acceptable range of 65% to 72%. The large dry region at the top of the part far exceeded the acceptance criteria of porosity, air bubbles, and dry spots in Section 3.2.1. There were also large voids (up to 30mm length, 3mm width) within the foam core draping slits (grooves that are perpendicular to the tool within the foam core in Figure 83A and C) in the upper half of the part. It was not possible to see how deep within the structure these voids extended. Void size appeared similar on both sides of the part, indicating that these defects potentially extend through the entire width. These slits had initially completely filled with resin during the infusion process, so it is thought that the resin had drained from these regions during the time between the infusion shut-off and resin gelation. There are no specific defect criteria that directly apply to the foam core (defect acceptance in Table 2 is focused on composite laminates). In the absence of detailed structural analysis of the effect of these defects, it is not possible to generate an accurate value for defect acceptance in this region for this specific case study. As a conservative first approach, these open channels in the foam core are evaluated using relevant defect criteria outlined in Table 2 (air bubble >3mm diameter and no foreign inclusions). The voids in the part exceed 3mm diameter, and therefore do not conform to acceptance criteria.

Overall, this infusion trial was a success. The infusion process was conducted within the 8-hour goal and the part produced was of an acceptable quality. It is proposed that the resin gelation time and infusion time be more closely matched to address the dry region at the top of the part and voidage within the foam core. Previously identified layup tolerances were achievable for this narrow section. No modifications are proposed to these tolerances at this stage as the demonstrator manufacture is considered to be more challenging (i.e., handling 1.2m wide plies and implementing splice joints). Table 34 compares the process against the previously identified requirements. Based on this evaluation, the manufacturing process is deemed acceptable for the demonstrator production (with the proposed modifications).

Table 34: Evaluation of final infusion trial against relevant process requirements

Process requirements		Proposed scheme
Name	**Value**	**Value**
Maximum infusion duration	8 hours	6 hours
Laminate fibre weight fraction	65% - 72%	67.7%
Longitudinal ply positioning tolerance	+/-30mm	+/-10mm
Lateral ply positioning tolerance	+/-10mm	+/-10mm
Acceptable defects	See Table 2.	Large dry region at top of part (1x0.4m). Numerous voids in foam core channels >3mm diameter

4.9 Conclusion

The work presented in this chapter builds on the methodology and findings of the previous chapter, detailing a rapid approach for developing a large-scale resin infusion process for a composite hull shell. The hull shell demonstrator design features monolithic and sandwich sections up to 275mm in thickness, is 9m in circumferential length and 6m in total height. A spiral development model was implemented to accelerate the research activity and focus the work on the key technical challenges and project requirements. Directly tackling these challenges early in the development process via representative tests with the selected materials reduced overall project risk. The flexibility of this model allowed the author to adapt each test according to the results of the previous test, reducing the need for repeated experiments and costly re-development activities. The work begins with small-scale experiments that consider simplistic resin flow in thin laminates and horizontal sections. As knowledge is gained through these tests, the experiments are incrementally expanded to consider more complex challenges such as thick monolithic and vertical sandwich infusions.

An infusion strategy was generated using the incremental knowledge gained from each experiment and validated via a final full-scale representative infusion trial. The final trial highlighted the issue of resin drainage within the vertical sandwich preform after the infusion had completed. The stationary liquid resin within the preform was able to drain downwards due to gravity in the period of time between ending the infusion and resin gelation. This resulted in a large region forming at the top of the part, and several smaller voids within the sandwich core. The resin cure time should therefore be modified to closely match the infusion duration, reducing the time over which this drainage can occur. Despite the two quality issues with the produced part, the process was shown to be a success and met all other process requirements (see Table 34). This process (with the suggested modification) is applied to the manufacture of the demonstrator in the next section.

The proposed process consists of several low-cost solutions to address the manufacturing challenges and meet process requirements. A simple material deposition tool and access gantries were developed to help laminators accurately position plies up to 9m in length on the curved tool surface. A low-cost degassing approach has been developed to reduce resin voidage levels (if required). A resin injection machine provides injection pressure to counter the hydrostatic pressures of a vertical infusion. This negates the need for potentially risky and unsafe procedures related to raising large containers of resin 3m up into the air. A series of key research questions were identified and answered throughout this process to support the development of this infusion strategy. These are listed in Table 35 and may act as a useful reference for other similar industrial research projects featuring the rapid development of a large infusion procedure. The methodology presented in this chapter may also be applicable to other large-scale infusion processes such as composite tidal turbine blades.

An experimental approach was selected over simulation to address the limited timeframe, industrial setting, and high-risk nature of this novel research project. The use of expert knowledge and prior manufacturing experience to identify and support suitable experiments proved to be a successful and cost-efficient approach. However, for future projects it is proposed that a combined experimental and simulation approach may offer further reductions in project duration and cost by replacing some of the practical experiments in this work with faster, more cost-efficient simulations. For example, the horizontal and vertical sandwich infusion trials could be replaced with simulation, provided the reinforcement permeabilities and core flow channels are accurately represented. However, the experimental findings relating to the practical manufacturing challenge (realistic layup procedures/tolerances, suitable time under vacuum prior to infusion) would not be identified using simulation. Incorporating this information from other projects within the capture of expert knowledge and prior experience may be one way to supplement further use of simulations. Overall, a company with the experience and resources available to conduct representative experimental tests and accurate simulations would be well suited for rapid infusion process development activities.

Table 35: List of key research questions used to guide the rapid development of a large-scale infusion process

1	What are the fundamental stages of research that are required to develop an infusion strategy for the selected case study?
2	What is the most suitable analytical approach for developing an infusion process for the selected case study?
3	What is the maximum height to which the resin can be lifted under vacuum?
4	What is the most suitable inlet and outlet configuration for infusing thin laminates of comparable geometry to the selected case study?
5	What is a suitable vacuum level range for the infusion process?
6	What is the effect of resin reservoir height on the infusion process?
7	How does the choice of tool or bag surface effect the infusion process?
8	How does the laminate thickness vary with height for a thin vertical infusion?
9	What is the most suitable inlet and outlet configuration for infusing large, thick sandwich sections of comparable geometry to the selected case study?
10	What is the most suitable inlet and outlet configuration for infusing large, thick monolithic sections of comparable geometry to the selected case study?
11	Can the proposed infusion schemes for individual regions of the part be combined to successfully produce a full-scale representative section?

The work in this chapter focuses on the key manufacturing challenges that were identified based upon the project requirements. It is important to note that there are some uncontrolled sources of error which are not addressed in this work due to the rapid development approach taken and the gaps in the project requirements. For example, ply positioning tolerances were not fully explored in this chapter due to the relatively small scale of the plies compared to those featured in the demonstrator. Variation in the compaction applied to each ply was also not quantified. Ply draping was also not considered, and draping simulations may be applied in future works to further explore the effect of this parameter on the infusion process. Ultimately, these variables were not considered in this work as they were deemed secondary issues to those that were addressed.

5 MANUFACTURE OF LARGE COMPOSITE MARINE STRUCTURES

5.1 Introduction

This chapter presents a full record of the manufacturing process used to create the full-scale composite hull shell demonstrator section. This work builds on the demonstrator design and infusion process developments presented in Chapters 3 and 4. The work focuses on the novel challenges related to laying up and infusing large composite sections of up to 6m in height and 275mm in thickness, with varying sectional geometry and structural features, including both sandwich sections and thick monolithic laminates. The purpose of this work is to generate knowledge through production of a demonstrator that can be used to develop a full-scale manufacturing process for a 75m long hull shell. The demonstrator manufacturing process is therefore reviewed at the end of this chapter, and a full-scale manufacturing concept is proposed, leading to future work. The work presented in this chapter was conducted as part of the RAMSSES EU research project. The author developed this manufacturing process with the aid of expert knowledge and experience available at Airborne UK and acted as both the engineering and production lead for this hull shell manufacturing study. The author also acted as a laminator and member of the production team throughout this study to maximise the practical knowledge gained. Discussions relating to the practicalities and evaluation of this process are therefore based upon the personal experiences of the author and the production staff that assisted with this project.

This chapter follows the manufacturing process from tool setup to finished product, primarily focusing on production methodologies that are compatible with the hull shell design. Detailed accounts of the individual process steps are provided alongside justifications for these decisions. A time-lapse video of the manufacturing process is available at: https://www.youtube.com/watch?v=QTUD4p7gm3M [Accessed Online: 12/10/20]. Further details of the demonstrator design, including ply stacking sequences and material selection can be found in Chapter 3. A summary of the hull shell demonstrator design is given in this introduction as a recap. The demonstrator section consists of 7 main segments:

- **Monolithic keel:** 275.4mm thick solid monolithic laminate positioned at the base of the demonstrator. This acts as the "backbone" of the ship.
- **SP1 (Sandwich Panel 1):** 249.6mm thick sandwich panel with 23.3mm thick laminate skins and a 203mm thick foam core. The foam core is built up using 4x 50mm thick foam layers with single 1mm Saerflow plies sandwiched between them.

- **Joint 1 monolithic support:** Solid monolithic laminate transitioning between SP1 and SP2. Thickness transitions from 203mm to 101mm, providing a ledge to support deck 1.
- **SP2 (Sandwich Panel 2):** 128mm thick sandwich panel with 13.6mm thick laminate skins and a 101mm thick foam core. The foam core is built up using 2x 50mm thick foam layers with a single 1mm Saerflow ply sandwiched between them.
- **Joint 2 shear web support:** Two 12mm thick laminate shear ties passing through the thickness of the structure, connecting the inner and outer skins. These shear ties help to distribute load from deck 2. A higher density foam (GR200) is positioned between the shear ties for additional support. A small monolithic wedge is positioned over the inner skin to create a ledge for deck 2.
- **SP3 (Sandwich Panel 3):** 87.1mm thick sandwich panel with 13.6mm thick laminate skins and a 60mm thick foam core. The foam core is built up using a single 50mm thick foam layer.
- **Joint 3 monolithic support:** A tapered monolithic laminate at the very top of the demonstrator to support deck 3. Thickness tapers from 87.1mm to 27.2mm. The resulting negative angle on the outer face provides a bonding area for the deck 3 joint.

5.2 Key challenges and project requirements

The most challenging steps of the manufacturing process were identified in Section 3.5 as being layup, vacuum bagging, and infusion. The following specific challenges were identified:

- Scale, Geometry, and Accessibility
- Vertical infusion
- Variable shipyard environment

The manufacture of the demonstrator in this chapter will be used to review whether these challenges have been addressed. This shall be done by evaluating the demonstrator production against the project requirements outlined in Section 3.9. The work presented in Chapter 4 shows how many of these requirements can be met using the proposed resin infusion process. This chapter will verify if this is true when scaled up to the demonstrator section. In addition, this chapter shall also explore the remaining requirements relating to ply positioning tolerances and the potential formation of laminate defects due to the challenges of laying up large (up to 2.3m wide) continuous plies over the 9.1m x 2.3m curved tool geometry. The manufacturing process and infused demonstrator part shall be evaluated against the full list of project requirements, and where applicable, the suitability of these requirements will be reviewed alongside suggested improvements to the process.

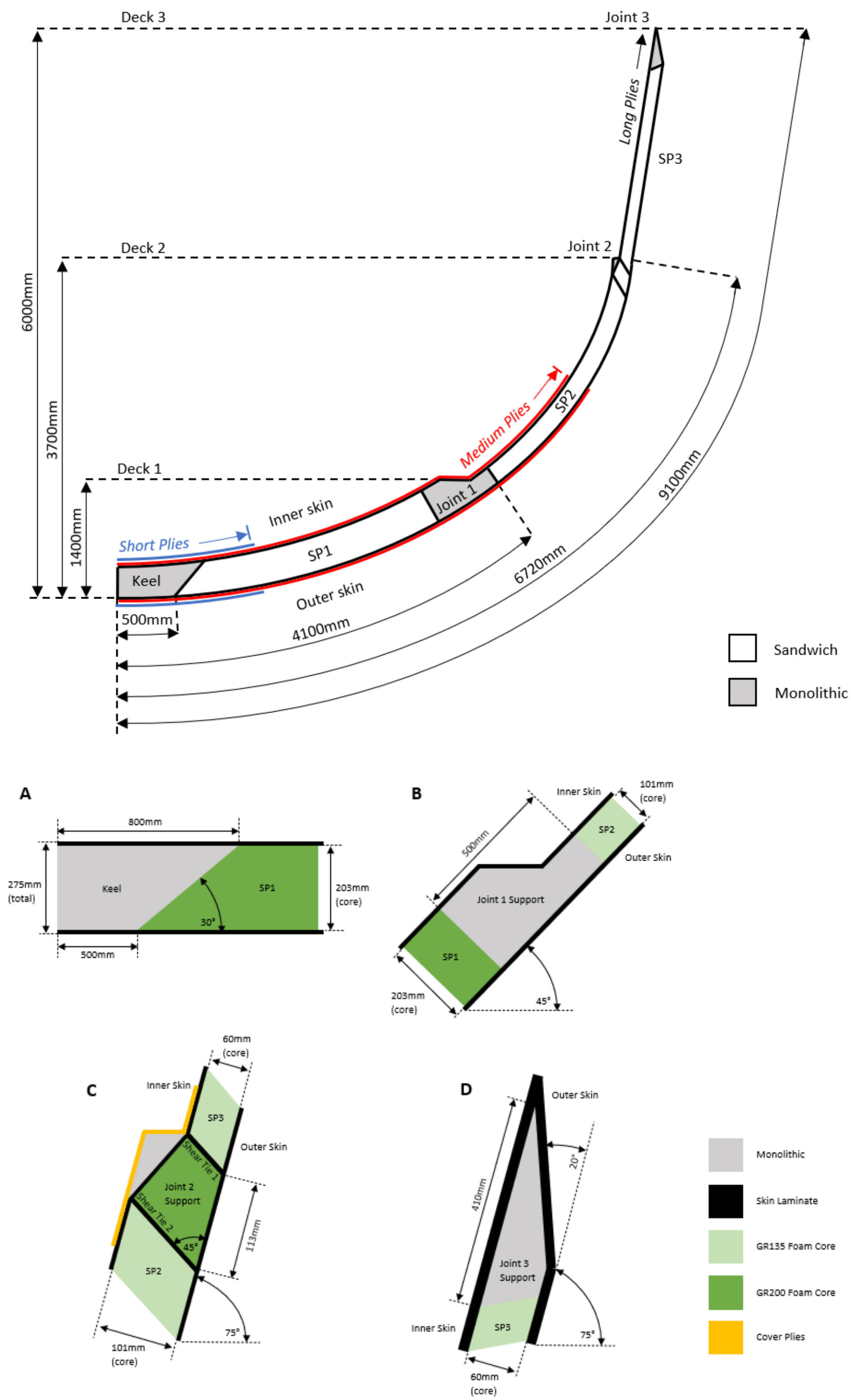


Figure 85: Demonstrator hull shell design (drawings not to scale)

5.3 Manufacturing process flow chart

The flow chart in Figure 86 outlines the simplified manufacturing process for the demonstrator hull shell. The format of this chapter follows this flow chart from initial setup through to the finished product. This flow chart is further refined as the demonstrator is manufactured, and a revised version is presented at the end of this chapter.

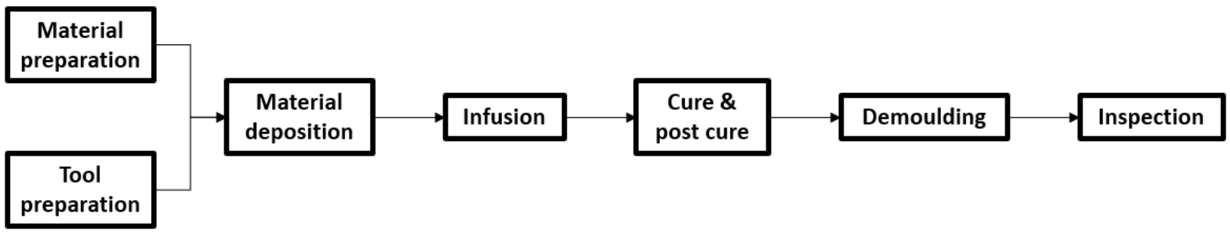


Figure 86: Manufacturing process outline

The flow chart displays repeatable tasks only. Tool creation and infrastructure setup are non-repeatable tasks that are conducted at the start of the process, whereas all other steps in this process are repeatable.

5.4 Tool Design and Supporting Infrastructure

This section describes the work done at Airborne UK to develop and install the necessary equipment for demonstrator production.

5.4.1 Tool Design and Installation

The demonstrator tool was designed and produced by DAMEN shipyards. The tool was designed to fit onto a flat-bed truck to minimise transport costs. Because of this, the demonstrator is limited to 2.5m width and the centre-most portion of the keel is removed. The tool is made from steel for robustness and durability, given that it will be transported from NL to UK and used to produce multiple trial mouldings in addition to the final demonstrator. Alternative materials include plywood and foam tooling block which are commonly used for one-off yacht building. Whilst tools using these materials may be cheaper to produce, there is more uncertainty and risk associated with long-term durability and tool stiffness/deflection during layup (preform mass is approximately 2 tonnes).

The tool was installed at Airborne UK upon delivery from DAMEN shipyards. A vacuum integrity test was performed over the entire tool surface to check whether the steel tool surface could hold a sufficient vacuum level, and if tacky tape could be used to form a reliable vacuum seal between the tool surface and vacuum bag after release agent has been applied to the tool.

Results of the test concluded that the release agent must be removed locally where the tacky tape is applied to create a reliable seal. It was possible to achieve a vacuum level of -0.9521 bar after 8 hours with a single vacuum bag over the entire tool surface. Breather cloth was placed underneath the vacuum bag to improve airflow to the vacuum pump. The vacuum bag was disconnected from the vacuum pump and left for 24 hours. During this time, the vacuum level within the bag dropped by 1.4% to -0.9386 bar. The results of this test confirm that the tooling, vacuum bag, and tacky tape are sufficient to produce a good seal for demonstrator production.

Once installed, only the bottom region of the tool surface was accessible to the workforce, posing serious challenges for production. To overcome this, three key supporting infrastructures were developed and installed at Airborne UK to improve human accessibility and material deposition capability.

5.4.2 Access Gantry and Scaffold Tower

A two-tiered access gantry was created to provide access to the middle region of the tool surface. Wheels were attached to the bottom of the gantry to allow flexible positioning during various stages of the manufacturing process. A scaffold tower was also constructed at the back of the tool to provide access to the very top region of the tool surface. This was permanently fixed to the tool. Figure 87 shows the setup.

Figure 87: Gantry and scaffold tower installed around demonstrator tool

5.4.3 Material Deposition Tool

The gantry and scaffolding provide sufficient access to most of the tool surface, however there are some regions above and below the gantry that cannot be reached by humans safely. Furthermore, multiple laminators handling large plies across different levels of the gantry and/or scaffolding is both impractical, time consuming, and unsafe. Therefore, a material deposition tool was developed and mounted to the demonstrator tool to streamline the layup of glass reinforcement across the tool surface. The purpose of this deposition tool is to quickly and easily deposit plies of glass reinforcement anywhere on the demonstrator tool surface. The tool consists of two electrically driven winches mounted at the top of the tool that lift an aluminium tube supporting the rolls of glass reinforcement. This setup is shown in Figure 88.

Figure 88: Testing material deposition tool during penultimate trial

5.5 Tool Preparation

Prior to any work being carried out, the demonstrator tool was thoroughly cleaned with warm soapy water to remove dust and general contaminants which were added during transportation. The tool was then rinsed with water and allowed to air dry before applying release agent. This proved to be a cost-effective method for cleaning large-scale tooling.

5 coats of “Marbo FF 321/1 COD 64” release agent were applied to the entire tool surface by hand using extendable rollers. The release agent was evenly applied and left to dry between coats. The slight white colour of the release agent allowed the applicator to see which areas had been coated, helping to ensure complete surface coverage.

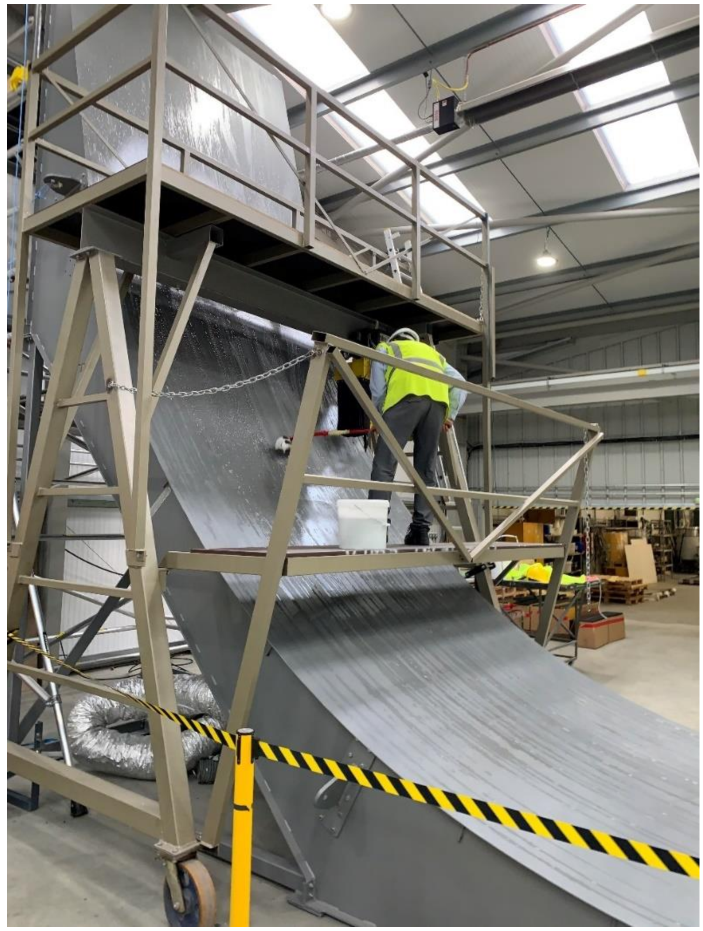


Figure 89: Cleaning demonstrator tool

5.6 Material Preparation

This section outlines the steps taken to convert the raw constituent materials as delivered into usable forms ready for production.

5.6.1 Reinforcement Preparation

The proposed layup for the demonstrator section was outlined in chapter 3. In summary, plies cut to specified widths and connected via splice joints that are distributed throughout the stacking sequence. These splice joints are offset across the demonstrator width to avoid alignment and thus continuous seams through the structure. The required ply widths and stacking sequence is provided in Table 21, and the reader is encouraged to refer back to Section 3.8 for further details. To achieve this pattern with the material deposition tool, rolls of material were pre-cut to specified widths using a reciprocating saw. The pre-cut rolls could then be loaded into the material deposition tool quickly during the layup procedure to achieve the desired ply pattern. To reduce the risk of fibres fraying during cutting, rolls were pre-compacted around the cut line using several rounds of masking tape. The saw blade and material roll were continually repositioned so that the cut was made normal to the roll surface. Cutting into the roll this way reduces the risk of fibre fraying. Figure 90 shows a roll of glass reinforcement cut using this method.

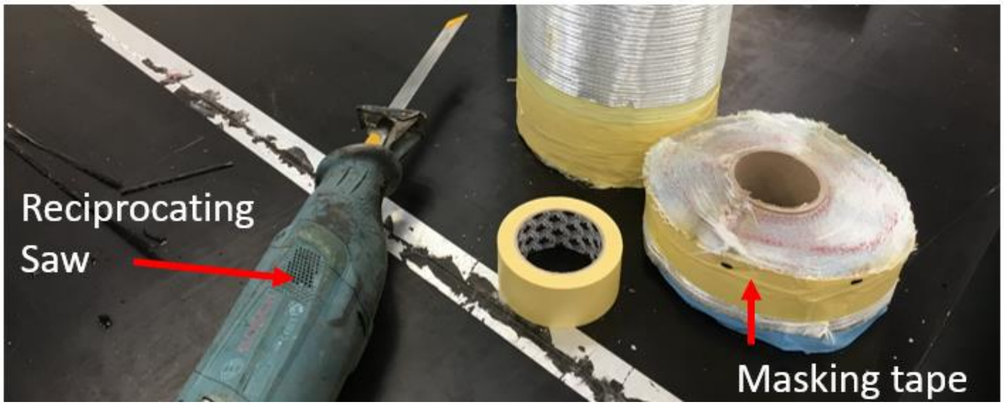


Figure 90: First attempt at cutting glass reinforcement rolls

It should be noted that not all rolls were cut to reduced widths. Table 21 outlines that some plies in the stacking sequence are the same width as the supplied roll width. These plies were laid up directly onto the part with no modifications or cutting. The demonstrator preform therefore features ply splice joints with un-cut ply edges. These edges are often removed prior to layup in high-performance applications due to concerns over frayed edges and their effect on the structural performance of the part. However, these edges were not removed due to the following reasons:

- It was not possible to accurately remove a small slice (~5mm) off the edge of the rolls without causing further damage to the edges of the plies using the manual method outlined above. A large section of the material would need to be cut from the roll, leading to further material waste and a need to modify the ply layup sequence.
- The ply positioning tolerance for 9m long plies over a curved and vertically inclined tool surface with limited accessibility was considered to have a far greater effect on the local laminate quality around the splice joints. Furthermore, the edges of the plies on the roll did not appear to be damaged or significantly frayed, and an acceptable ply splice joint quality is not specifically defined in the acceptance criteria. More detailed investigations into acceptable ply edge quality within the structural laminates is therefore left for future work.

5.6.2 Resin Preparation

The resin components must be mixed before infusion. The resin must also be mixed periodically to ensure the toughening component remains evenly suspended within the resin. To achieve these goals the following resin preparation setup was developed. The resin is a three-part mixture, consisting of 100% Albidur, 1% Weloxan and 0.25% Pergaquick. The only available resin injection machine was configured to accept a two-part mixture. Therefore, the two-part mixture outlined in Table 36 was prepared for the injection machine. These mixtures overcome limitations of the injection machine and were pre-mixed prior to infusion.

Table 36: Practical resin mixture.

Mix	% of mix used	Components in mix	% of component in mix
Mixture 1	100%	Albidur	100%
		Weloxan	1%
Mixture 2	1%	Albidur	75%
		Pergaquick	25%

Mixture 1 was prepared in the IBC. A mixing head was installed within the IBC to stir the contents. Weloxan was added to the IBC because it was too viscous to pass through the injection machine pumps alone. Mixture 1 dilutes the Weloxan and hence reduces the viscosity of liquid passing through the pumps. The mixing head is also used to disperse the toughening particles before and during the infusion.

Mixture 2 was hand mixed in a 20-litre bucket. The lowest mix-ratio achievable with the injection machine was 0.5% accelerator to 100% resin, however a ratio of 0.25% accelerator to 100% resin was required. To achieve the required 0.25% ratio, the Pergaquick was diluted with resin to produce mixture 2. The resin mixing procedure is shown in Figure 91.

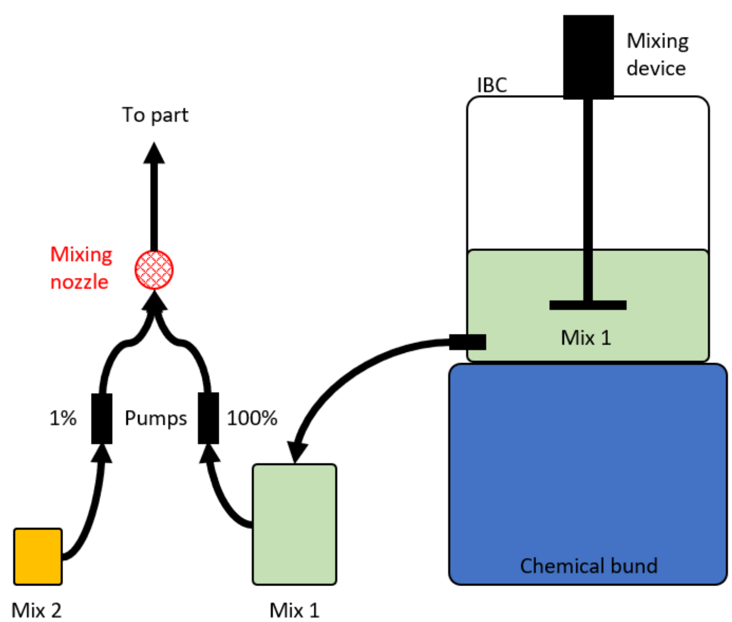


Figure 91: Resin mixing procedure

5.6.3 Foam Core Preparation

The foam panels were supplied with flow channels, draping slits and through-thickness perforations. These features are shown in Figure 92. The flow channels are aligned up the length of the demonstrator to aid resin flow during infusion. The perforations create channels between the top and bottom skins, normalising the resin flow front through the section thickness. Draping slits are aligned across the width of the part and allow the foam sheets to drape to the curvature of the tool.

The foam panels were cut to size and shape during the core layup procedure. Chamfers were machined to provide sectional interfaces as outlined in Figure 85. These tasks were performed alongside the foam layup as each foam panel was custom made to fit the structure and match the foam layup pattern. This was done to avoid misalignment of foam panels due to cutting and measuring tolerances, which is possible considering the size of this one-off prototype structure.

A single ply of Saerflow was applied to the edges of the panels to ensure good wet-out between foam panels and prevent any dry areas/discontinuities within the structure. The Saerflow strips were fixed to the foam edges using composite staples. This process was also conducted whilst the foam sheets were being laid onto the tool as some panels required Saerflow strips on different edges (to avoid duplicate Saerflow layers between foam sheets). Figure 92 displays all of these details.

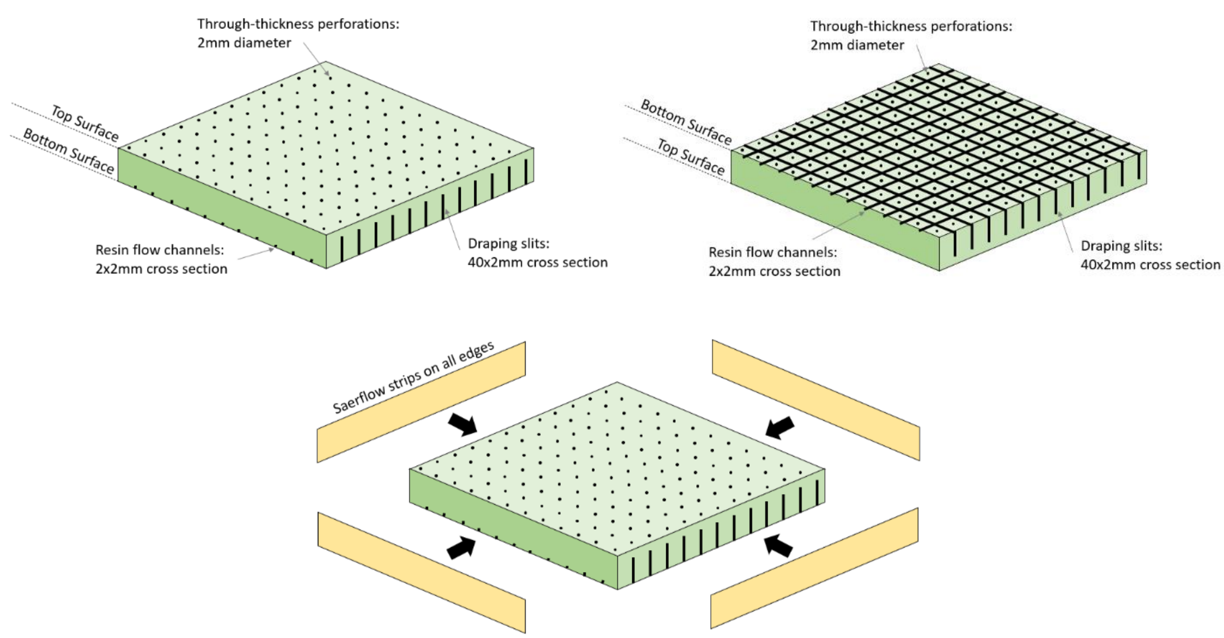


Figure 92: Foam core panel details

5.7 Material Deposition

This section describes the key procedural steps undertaken to create the dry preform. The key novel challenges addressed in this section are the handling and layup of large reinforcement plies on near-vertical tool surfaces. Materials are laid onto the tool in a sequential manner, starting with the outer skin, followed by the structural core and then the inner skin. Structural core elements are laid up sequentially from the keel upwards. This task poses two major challenges; creating a stable preform that can support its own weight and handling/ layup of large continuous plies on a tool surface with limited accessibility. The processes described in this section adhere to the manufacturing design outlined in Chapter 3. The reader is encouraged to refer back to this work for further information on the rationale behind the demonstrator design.

5.7.1 Outer Skin Layup

Layup of the outer laminate skin utilised the material deposition tool that was described in a previous section. The plies were laid onto the tool as prescribed in the ply book. Whilst these plies were split in the width direction to accommodate the limited roll widths, they were always continuous up the length/circumference of the tool to maximise the structural efficiency of the fibres. The outer skin consists of full-length, medium and short plies, alternating between each throughout the layup sequence. The following layup procedure was determined to be the most efficient after some trial and error. Individual workforce roles are highlighted in bold. In total, four staff were required to efficiently layup the laminate skins. The skin layup is split into two distinct procedures depending on the length of ply.

5.7.1.1 Continuous Full-Length Plies

The procedure starts with the **ground team, consisting of two laminators**, loading the correct roll configuration onto the material deposition roller. The rolls of glass reinforcement are taped to prevent unravelling. A signal is then given to the **winch operator** at the top of the scaffolding to raise the roller to the very top of the tool. The winch operator removes the tape and begins unravelling the glass rolls one at a time. As the rolls unravel, the end of the glass ply extends downwards towards the keel. The ground team position the end of the ply at the keel. At the same time a **third laminator at gantry level** positions the middle section of the ply on the tool. The winch operator then cuts the top of the ply from the roll and position the top edge of the ply onto the tool. A 300mm excess is included at the top of the ply and is folded over the top edge of the tool, preventing the ply from sliding downwards over time due to gravity. This excess also acted as a resin reservoir during infusion and is discussed in more detail in the following infusion section of this report.

Upon confirmation from all team members that the ply is correctly aligned and positioned, the gantry laminator begins removing the backing film and laying up the ply, starting from the middle of the laminate and moving upwards towards the top. At the same time one member of the ground team does the same, working down towards the keel from the middle position. This process is displayed in Figure 93. Starting at the middle and moving outwards in this way reduces the risk of fibre wrinkles, bridging and ply misalignment, whilst increasing layup efficiency by allowing multiple laminators to work simultaneously. Each ply is laid up using a hand operated roller to evenly apply compaction. The adhesive backing on each ply prevents the ply from slipping or moving once laid onto the tool.

Whilst the two laminators are progressively laying up the ply towards each end, the winch operator and second member of the ground team apply light tension at the top and bottom edges of the ply respectively. This helps to remove any large wrinkles as the ply is being laid down onto the tool. Once the ply has been fully laid up, a final inspection is performed by all team members to confirm alignment and lack of major defects. This process is repeated for all full-length plies.

Saerflow plies, used to aid resin flow, were also laid up in a similar manner to the quadaxial material. However, because the Saerflow was not supplied with adhesive backing, a spray adhesive was applied by hand to stick these plies to the preform. This was difficult due to the limited accessibility of some regions.

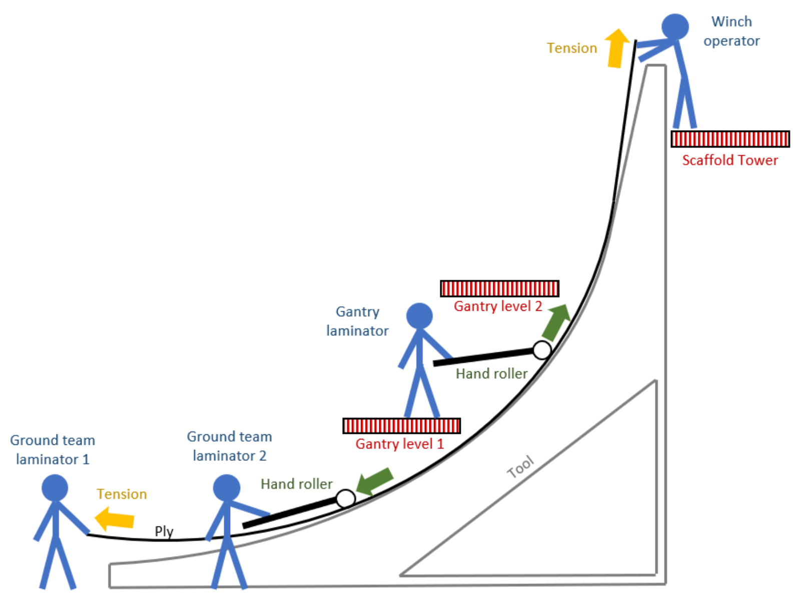


Figure 93: Layup procedure for full-length plies

5.7.1.2 Medium and Short Plies

Whilst the material deposition tool greatly improves handling of the full-length plies, changing out roll configurations after every ply can be time consuming and inefficient. Therefore, it is preferred to avoid using the material deposition tool where possible to improve time efficiency. The structural design outlined in chapter 3 features medium and short skin laminate plies which do not extend the full circumferential length of the tool. Figure 85 shows the position of the short and medium plies, which range from <1m to ~5m in length and can be handled by at least 2 laminators fairly easily.

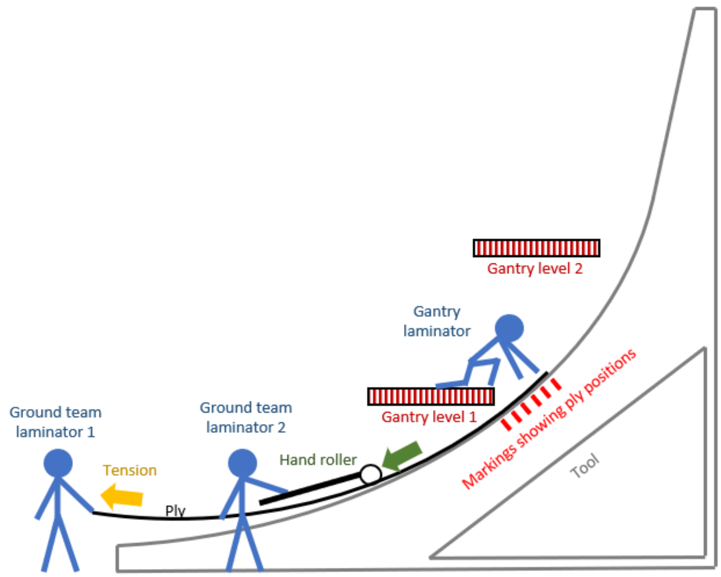


Figure 94: Layup procedure for medium-length plies

To accelerate the skin layup, it was decided that the medium and short plies would be pre-cut and ordered into kits prior to layup to allow for rapid hand layup during production, as shown in Figure 94. It is estimated that the overall layup process duration was reduced by 7 days using this method. The top position of every medium and short ply was marked on the edge of the tool. These markings were used to position each ply on the tool laying up each ply from the top downwards. This task was less intensive than the full-length plies, providing time for one team member to prepare roll configurations and perform general clean up tasks.

Figure 95: Layup of outer skin, showing ply staggering across the width and both short and medium plies

Figure 95 shows the plies that make up the outer skin laminate. The image shows the splice joints between plies running up the circumferential length of the part. In the top left of the image, one can see a width-wise gap between plies of approximately 20mm (the gap can be identified as a brighter white line compared to the surrounding glass reinforcement). This was the largest gap observed in the preform and demonstrates that the +/-10mm lateral positioning tolerance initialled predicted using expert opinion was accurate. On the right side of the image one can see a variation in ply edge position which extends 30mm into the edge of the laminate. This is due to compounding ply positional tolerances across the preform width (a maximum of 3 plies with a tolerance of +/-10mm equates to a +/-30mm edge variation). This was accounted for in the ply design by ensuring the preform is 60mm wider than the desired 2.3m part. 30mm is therefore trimmed off each edge prior to infusion, providing a tidy and uniform laminate edge.

Upon completion of the outer skin layup, a vacuum bag was applied and the entire skin debulked for 24 hours. This debulking procedure helped to stick the outer skin to the tool in preparation for the core layup. This debulking step also reduces the severity of wrinkles within the inner skin later in the process. Figure 96 shows this procedure.

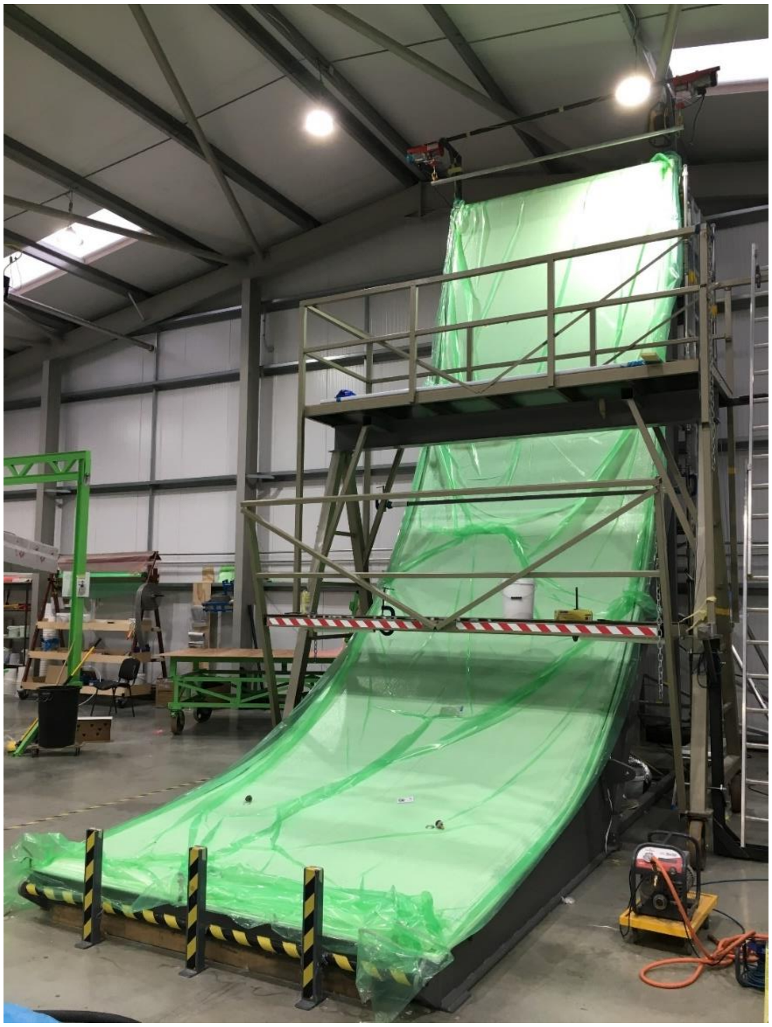


Figure 96: Debulking of outer skin

5.7.2 Formation of monolithic keel preform

The monolithic core addresses the novel manufacturing challenge of creating a 280mm thick infused monolithic structure. The monolithic keel core (excluding inner and outer skins) consists of 242 plies of glass stacked uniformly to form a solid laminate brick 0.5m long by 2.3m wide. The outer and inner skins envelop this solid core on either side to produce the full section thickness. The monolithic core has a 30-degree taper on one end where it meets the adjacent foam core. This transition poses an interesting challenge; the monolithic core is much thicker than the adjacent foam core prior to application of vacuum. If the inner skin is laid up over this transition, the sudden change in thickness will cause large wrinkles to form when vacuum is applied. This phenomenon is shown in Figure 97.

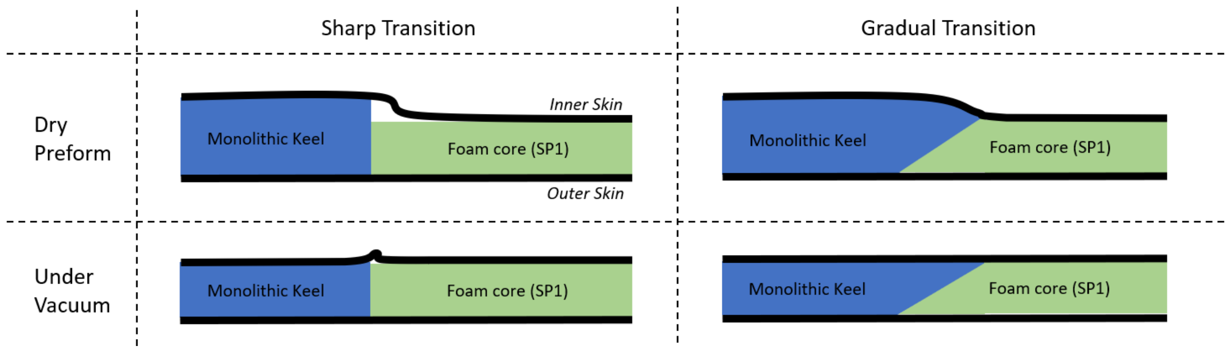


Figure 97: Skin wrinkling due to monolithic keel bulk factor

Implementing a 30° taper at the monolithic-to-foam interface as shown in Figure 97 spreads the thickness change over 300mm rather than a sudden step. This taper creates a gentle curved transition between monolithic and sandwich, preventing a wrinkle from forming in the inner skin. The monolithic keel is also debulked prior to layup to further reduce the likelihood and severity of wrinkles in the inner skin.

Previous debulking trials highlighted the beneficial, albeit minimal effect of debulking thick laminates. Debulking, together with the 30-degree tapered interface between the monolithic and foam cores have been shown to prevent any significant wrinkling in the inner skin during the penultimate infusion trial. However, debulking the monolithic core on the demonstrator tool is not time efficient. Instead, the monolithic core was laid up on a separate flat tool surface in parallel with the outer skin layup, reducing total production duration by approximately 3 days. The monolithic core was split into three sections of equal thickness to allow easier transportation to the demonstrator tool, as the total weight of the monolithic core preform is approximately 430kg. Figure 98 shows the procedure for creating the monolithic core.

Figure 98D shows the completed monolithic keel and adjacent SP1 sandwich core. In this image the edges of the outer skin have been trimmed to remove stray fibres. The plies within the monolithic keel “core” appear to be well aligned with one-another, with the edges of these plies positioned within the +/-10mm positioning tolerance, both in the longitudinal and lateral directions. The edges of the outer skin, monolithic core and foam sheets are shown to align within 10mm in Figure 98D. However, Figure 98C shows a slight misalignment between these sections on the opposite side of the preform, with a maximum variation of 20mm between the monolithic core and outer skin edges. This is primarily due to the fact that the outer skin has not been trimmed back enough at this stage. Overall, despite the weight of the monolithic keel preform and the difficulties of manual positioning these large sections, it appears that the proposed layup procedure was able to meet the predicted layup tolerances.

Figure 98B & C highlight the formation of a potential defect in the monolithic preform. These images show small linear indentations in the preform that run along the length of the part. These formed as the material was compacted under vacuum. Gaps between plies at the splice joints, and their alignment through the laminate (due to the ply pattern) results in a local reduction in laminate thickness. This may result in surface defects within the cured laminate. The effect of this feature on laminate quality and acceptability is discussed at the end of this chapter.

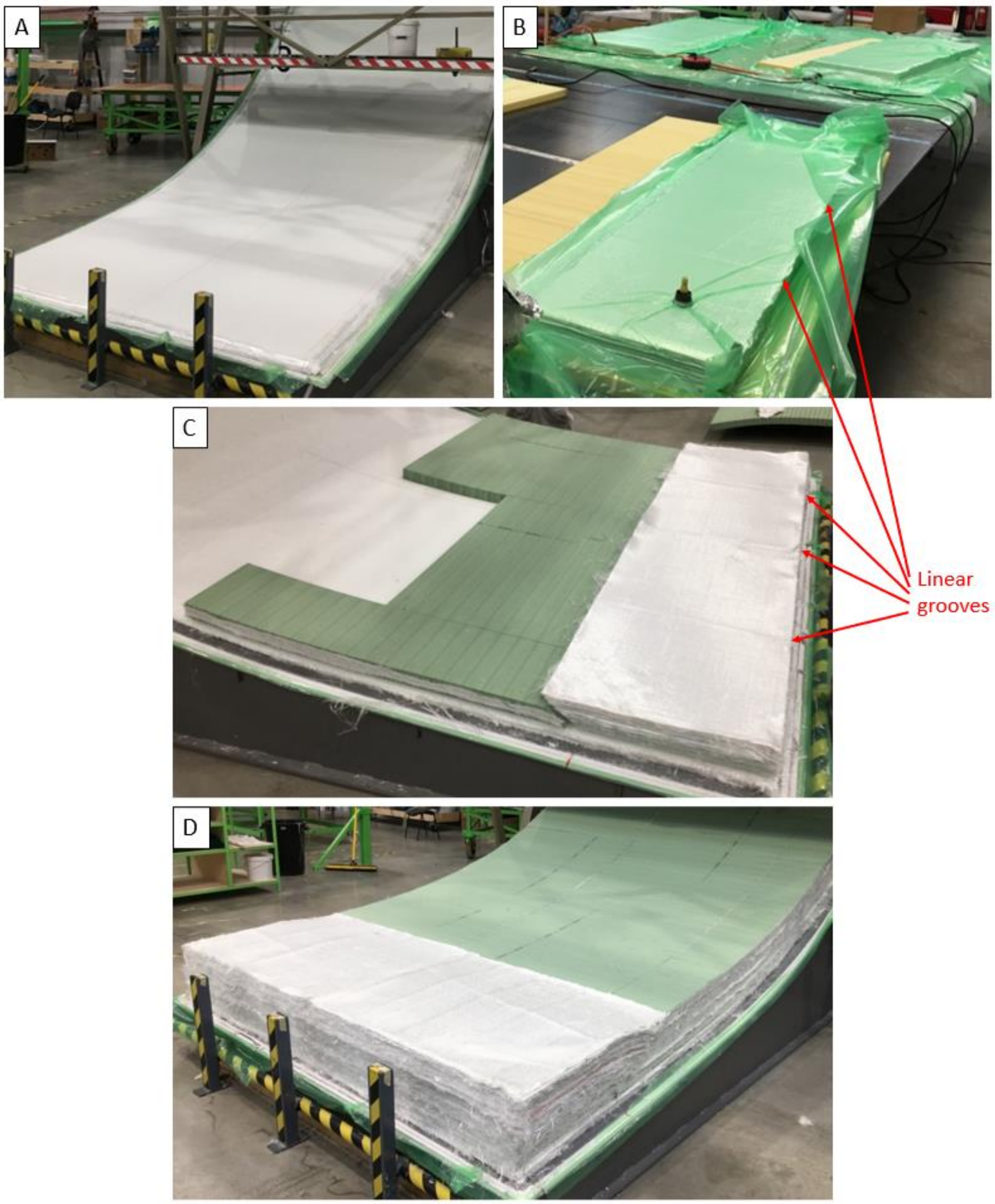


Figure 98: A: Outer skin layup, B: Three-part monolithic keel preform, C: Partial layup of keel and SP1 on tool, D: Monolithic keel and SP1 layup completed.

5.7.3 Foam Core Layup

The foam core layup addresses the novel manufacturing challenge of creating thick (87-250mm) and stable sandwich panel preforms on inclined (in some cases near-vertical) tool surfaces. Foam panels were positioned onto the tool by hand. Starting at the keel interface, foam panels were laid onto the tool in an alternating pattern moving up the tool in a fashion similar to bricklaying. This pattern is shown in Figure 98C. The chamfered edges of the foam panels were pushed up against the monolithic keel to produce a uniform transition as shown in Figure 98D. No adhesive spray or backing was required to hold the foam panels in place. The geometry of the tool and friction between foam panels were enough to keep the preform in place. The lower foam panels and monolithic keel supported the weight of the upper sections with minimal movement over the entire layup and bagging procedure.

The total foam core thickness was built up in layers sequentially from the outer skin upwards. Single 2.3m wide plies of Saerflow were laid between foam layers to aid resin flow and wet-out. For example, the layup sequence for the SP1 foam core was: [foam, Saerflow, foam, Saerflow, foam, Saerflow, foam]. This significantly reduced the risk of dry regions between foam sheets. The sandwich core was laid up sequentially from the keel to the top of the part. The layup process for the sandwich panels SP2 and SP3 were the same as described for SP1 above. The reader is encouraged to refer back to Figure 85 for an overview of the different features within the hull shell structure.

Foam sheets were tightly packed together by hand to minimise the gap between them. The presence of Saerflow between the sheets allowed the laminators to push the sheets together without worrying about closing/locking off resin flow channels. A gap of 1-5mm was achievable between foam sheets throughout the demonstrator. The weight of the upper preform meant that the gaps between foam sheets spanning the width-wise/lateral direction were generally smaller than those spanning the longitudinal direction.

The processes for creating the three remaining joint support features are explained below. Each joint support is different, and together they represent three different manufacturing methods for creating local through-thickness reinforcement in large composite sandwich structures. This approach enables a greater understanding of the advantages and disadvantages of each method to be gained to aid future designs.

5.7.4 Formation of Joint 1 Support

This support features a solid monolithic region 500mm long spanning the full width of the part. The debulking trials conducted previously indicate that it is not possible to layup this section on the tool as a dry preform due to the sudden change in thickness causing a large wrinkle in the inner skin, as shown in

Figure 97. Unlike for the monolithic keel, it is not possible to include a shallow transition angle to distribute this change in thickness over a given distance. This is because the tool surface at Joint 1 is inclined at 45 degrees, so a flat transition surface is required to support the weight of the materials above and prevent the preform from collapsing. Any significant transition angle here would cause the upper preform to slip and collapse under gravity. Further information on this decision can be found in Section 3.8.

To avoid wrinkles forming in the inner skin it was decided that the monolithic section must be the same thickness as the adjacent foam core during layup. The only feasible way to accomplish this was to use a pre-cured monolithic block that would not change thickness under vacuum. To do this, the joint 1 monolithic support was infused and cured on a secondary tool and then positioned on the tool during demonstrator layup. A secondary tool was created to replicate the local curvature of the demonstrator tool surface. This tool consisted of a 5mm thick aluminium sheet that was supported underneath by several steel beams of varying cross-sectional dimensions to create the desired curvature. The monolithic preform was laid up and infused on this tool as shown in Figure 99A. The part was infused using the in-plane infusion scheme previously identified in Section 4.6. The preform was left to cure at room temperature for 48 hours. Two lifting pins were then fitted into the top surface of the block to facilitate lifting and positioning on the demonstrator tool using a 7-tonne overhead gantry crane. This procedure is shown in Figure 99B and was the only identified way to safely manoeuvre such a heavy section into the required raised and inclined position using the equipment and resources available in a typical factory/shipyard. These pins were approximately 10mm in diameter and extended half-way into the total thickness of the monolithic laminate. Even if later removed, these pins resulted in the formation of unacceptable defects. The defect acceptance criteria states that no foreign metallic objects are acceptable within the part, and that no resin-pockets greater than 6.5mm diameter are acceptable.

The lifting pins could not be removed from the laminate without causing excessive damage. The pins were therefore cut down to be flush with the laminate. As this was the only feasible way to move the part into position during the demonstrator production, a solution to this issue of non-compliance is left for future work. Further structural analysis of this section could model these pins as holes within the laminate to identify whether the local stress concentrations are acceptable from a design perspective, and thereby modify the acceptance criteria accordingly. Alternatively, a more novel lifting approach could be developed to avoid the need for lifting pins. Finally, the hull shell design could be modified to no longer feature a thick monolithic laminate at this location.

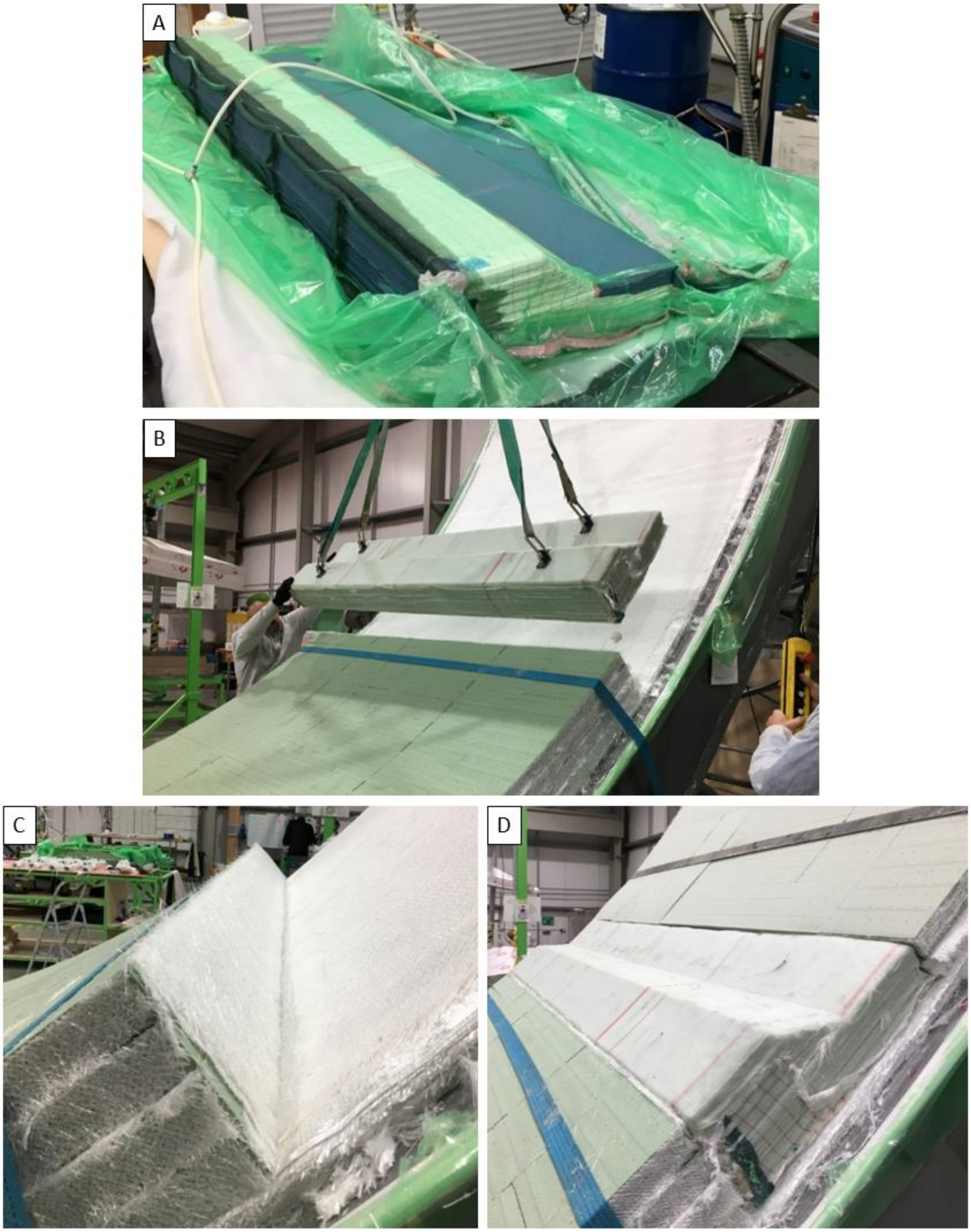


Figure 99: From top to bottom right: Infusion of joint 1 support, Positioning joint 1 support on tool, Two plies of Saerflow on top edge of SP1, Joint 1 support positioned between SP1 and SP2.

Two plies of Saerflow were positioned on the top edge of SP1, onto which the Joint 1 monolithic is placed (Figure 99C). These Saerflow plies ensure good resin wet-out between the foam and monolithic section.

With exception of the lifting pins, the general quality of the monolithic joint 1 insert was good based upon visual inspection. Ply alignment was within +/-10mm in both longitudinal and lateral directions. The implementation of gaps between ply edges at the splice joints resulted in the same linear grooves that were observed in the monolithic keel preform. The grooves were approximately 5mm in depth and 10mm in width after cure. It is not yet known at this stage whether the inner skin will fill these cavities (and thus create an inner surface geometry defect) or bridge over them (and create large resin pockets within the laminate). Either way, it appears this feature will likely create defects in the final part. This is explored in greater detail in Section 5.11. No other defects could be seen in the monolithic insert.

5.7.5 Formation of Joint 2 Support

The joint 2 support consists of two through-thickness shear ties with a high-density foam core situated between them. This support is located approximately 4m high off the ground so access to the tool surface is limited. To increase the efficiency of layup, this section was created in three parts, with the majority of the preforming work being conducted at ground level.

Figure 100 shows the proposed manufacturing process for this feature. Shear tie plies were wrapped around the foam cores to create robust preforms that are easy to layup. Adhesive backing held the plies in place on this near-vertical section of the demonstrator. Half of the plies were wrapped around the edges of SP2 and SP3 foam cores whilst the other half were wrapped around the joint 2 foam support. Distributing the plies in this way results in better load distribution throughout the local structure.

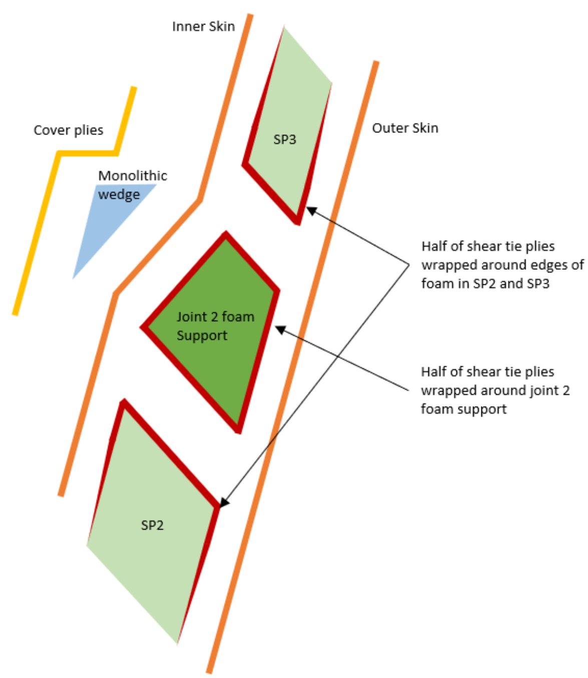


Figure 100: Joint 2 support manufacturing schematic

The central joint 2 foam support was created as a single 2.3m wide preform, which was then lifted into position on the demonstrator tool and aligned with the top edge of SP2. After the inner skin had been laid up a monolithic wedge was added to create a ledge to support deck 2. The geometry was created this way to avoid a sharp step in the inner skin, which, due to its thickness (13mm), would lead to severe wrinkles and fibre bridging. Four cover plies were used to envelop the wedge against the inner skin. Each cover ply was vertically offset my 80mm from the previous.

Figure 101 shows the key stages of creating this feature. In practice, it was difficult to tightly wrap the glass around the foam core insert. The weight/thickness of the fabric combined with the sharp geometric angles and 2.3m width of the part led to difficulties in matching the reinforcement to the core shape. The adhesive backing was insufficient in holding the reinforcement tightly in position, and the plies would eventually loosen slightly around the core insert prior to being positioned within the demonstrator preform. As a result, a slight fibre waviness can be seen in the wrapped plies when positioned on the demonstrator tool. This poses a significant wrinkling risk when vacuum compaction is applied. No alternative preform construction procedure was identified that was compatible with the available factory resources and the selected materials. A filament winding procedure could be a suitable alternative to the manual procedure featured in this report and may reduce the severity of any potential wrinkles that may form. This issue is explored in further detail in Section 5.11.

The monolithic wedge was found to be unsuitable for large-scale production as it required very long and thin strips of glass reinforcement which were difficult to stick together using the adhesive backing. This meant that the wedge preform, which was prepared at ground level and raised into position, was very delicate and distorted easily when handled. Application of vacuum compaction further deformed the section. After reviewing both the design and manufacturing process, it is not thought that this monolithic feature can be robustly produced to sufficient tolerances when scaled up to a full 75m long ship hull. Instead, it is suggested that the step is removed from the design entirely to allow a smooth transition between SP2 and SP3. This would require a redesign of the structure and bonding assembly.

5.7.6 Formation of Joint 3 Support

The main challenge of this feature was the layup of an 87mm thick monolithic laminate 6m up from ground level. As with the monolithic keel, this section was laid up and debulked as a preform at ground level before being lifted into position on the demonstrator tool. The preform was kept under vacuum as it was lifted to prevent it falling apart during the process. The winches were used to lift the bagged preform up the top of the scaffold tower, where two laminators carefully debagged and lowered the preform into position. The entire preform was wrapped in an envelope ply to prevent the preform from collapsing as it was lowered into position. The preform (within the envelope ply) is shown at the top of Figure 102.

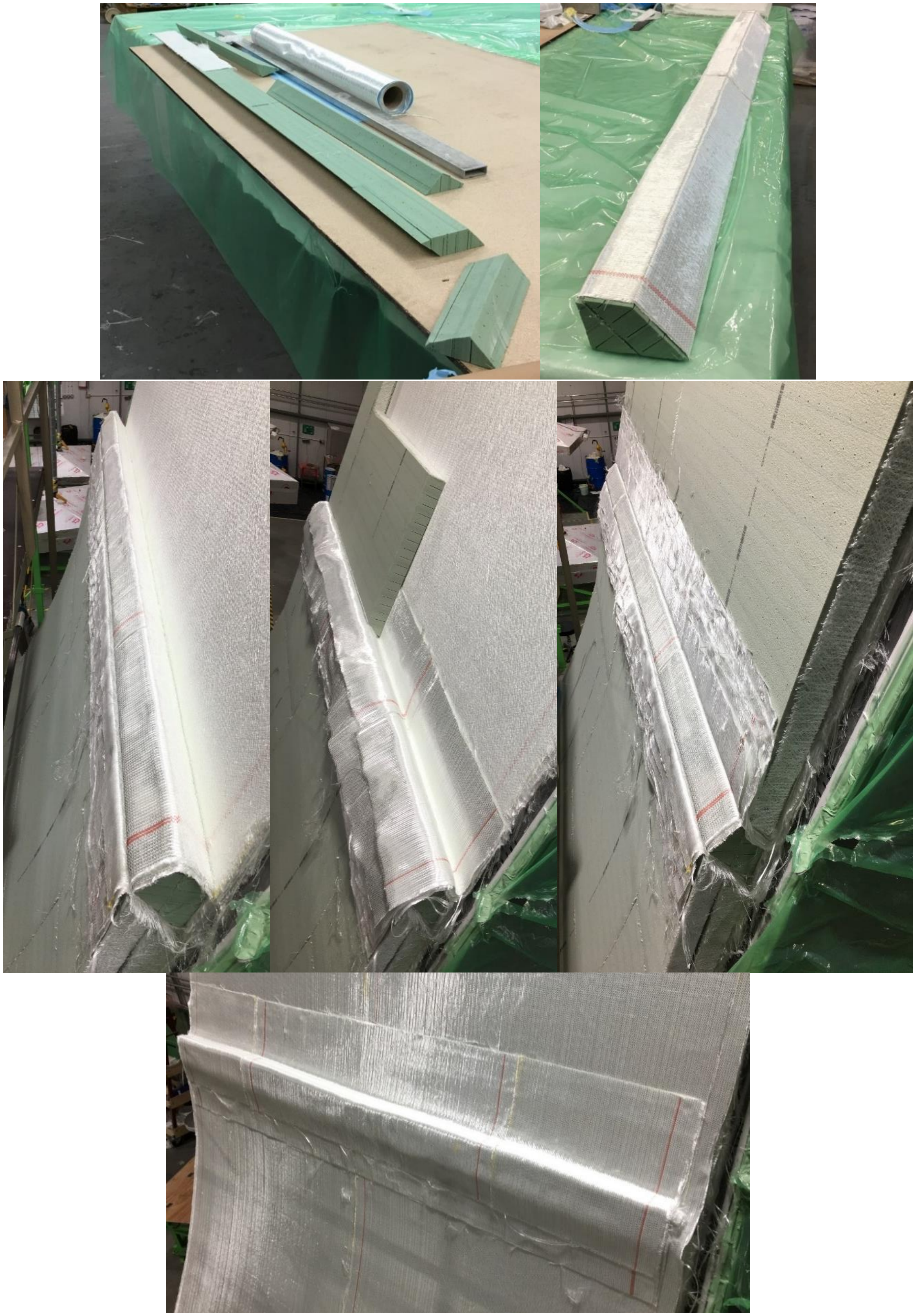


Figure 101: Joint 2 support layup. Photographs in order of production from top left to bottom right.

Due to the bulk factor of the monolithic preform, there was an approximate 9mm difference in thickness between the joint 3 monolithic section and the adjacent SP3 sandwich core. This change in thickness would theoretically be eliminated once vacuum compaction is applied. However, this detail poses a risk of wrinkles forming within the inner skin at this location. Furthermore, the vertical inclination and angled transition means that there is a risk of this preform moving slightly during the layup of the inner skin. Any downwards movement here would increase the thickness change and severity of wrinkles. To limit any downwards movement, the envelope plies were clamped over the top edge of the tool.

The process of positioning this monolithic region on the tool was both challenging and time-consuming. Limited accessibility to the SP3/joint 3 interface increased the challenge of aligning the two sections. Furthermore, the increased weight from the monolithic joint 3 support caused the foam panels lower down the demonstrator to buckle. This can be seen near the joint 1 and 2 supports in Figure 102. Two ratchet straps were used as a precaution to prevent the foam from collapsing, however the preform appeared stable and the straps were later removed prior to layup of the inner skin.

Figure 102: Outer skin and core layup completed

5.7.7 Inner Skin Layup

The layup process for the inner skin was conducted following the same steps previously outlined in the outer skin procedure. The layup of this skin posed some additional challenges due to the transitions in total sectional thickness at joints 1 and 2. The inner skin was prone to bridging at these locations. Poor accessibility combined with near-vertical inclination further exacerbated the issue. Extra care was taken to compact plies into the corners using extendable tools. Even so, fibre bridging was not completely avoidable, especially in the last few plies. The magnitude of fibre bridging was much greater in the demonstrator compared to previous infusion trials. This is because the previous trials were much narrower, and hence the plies were much easier to handle and layup. The use of adhesive backing and the large ply size meant that the individual plies could not easily slide over one another to eliminate this fibre bridging, even with vacuum compaction.

Figure 103: Potential for fibre bridging within the inner skin across joint 2 transition

The layup of the outer skin marks the completion of the demonstrator layup procedure. The entire part was bagged and debulked for 2 weeks (due to holidays). This vacuum bag was removed prior to the layup of infusion consumables. Figure 104 shows the debulked preform under vacuum.

5.8 Infusion

This section describes the infusion process that was used to produce the demonstrator section, particularly the small variations and improvements that were implemented using learning from the infusion trials. The reader is encouraged to refer to the previous infusion chapter for further reasoning behind the more fundamental aspects of this infusion process.

Figure 104: Completed demonstrator layup under vacuum

5.8.1 Setup of Infusion Consumables

5.8.1.1 Global infusion setup

The infusion was setup similar to the final infusion trial, which was an overall success. Nine resin inlets were distributed up the length of the demonstrator. Figure 105 shows the positions of each inlet on the tool. The inlet positions were decided by weighing up two important aspects:

Figure 105: Demonstrator ready to infuse, resin inlets highlighted in red

Firstly, inlets should be strategically placed at critical areas of the part where lock-offs are most likely. This generally means that inlets should be placed at transitions between discrete sections of the part where resin flow paths could become more complex.

Secondly, inlets should be distributed as evenly as possible to avoid long infusion paths which could lead to the resin curing before reaching the next inlet.

Each section of the part was infused sequentially starting from the open face of the keel at the base of the part and moving upwards. All inlets were connected to a single resin feed linked to the injection machine. In-line valves were used to separate each inlet on this network. This setup features two types of inlets which are discussed in more detail below.

5.8.1.2 Inlet configuration – Monolithic keel

Figure 106 shows the configuration for the monolithic keel resin inlet. Two layers of blue flow mesh were placed over the entire open face of the monolithic keel, with a network of spiral tube placed over the mesh to evenly distribute resin quickly across the surface. The combination of flow mesh and spiral tube creates a large resin reservoir across the entire surface.

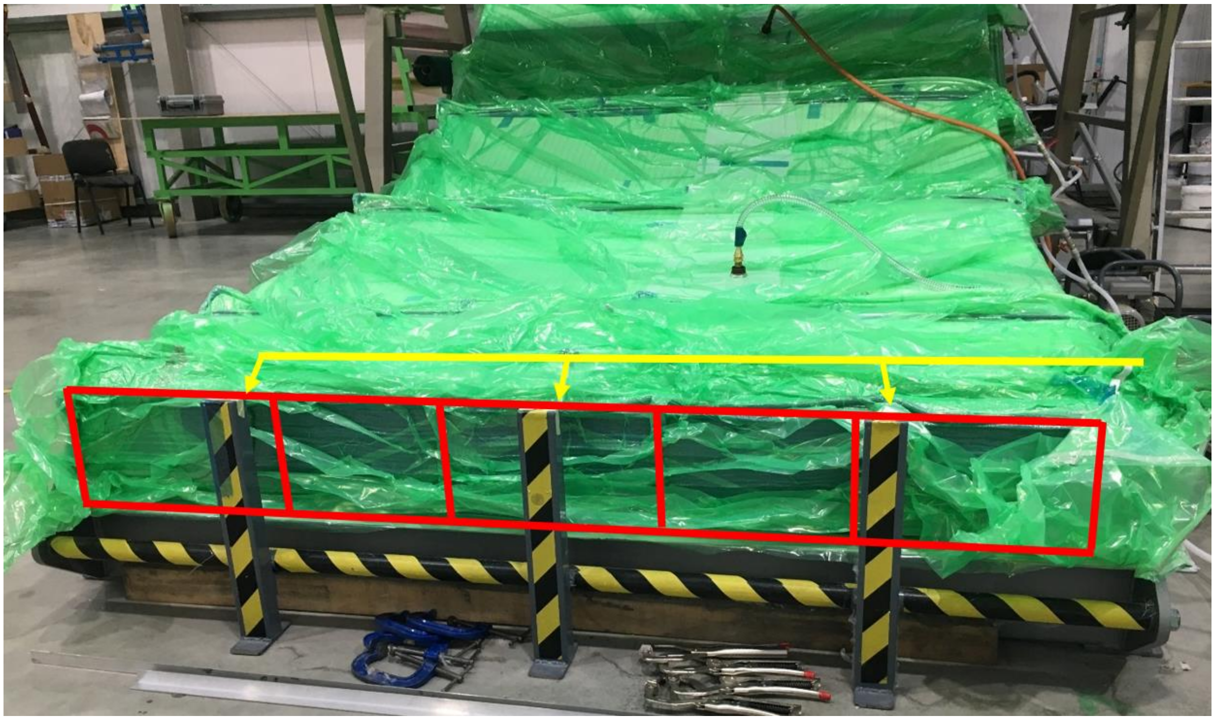


Figure 106: Monolithic keel resin inlet. Spiral tube network (red) and resin delivery tubes (yellow)

The spacing of the spiral tube network (i.e., distance between vertical spiral tubes) was 0.46m, identical to the penultimate infusion trial, which was shown to be successful. Resin was introduced to this inlet at the start of the infusion to create the uniform flow front which then travelled up the demonstrator. It is therefore important that this feature was setup properly as small blockages or misalignments could lead to a skewed flow front and issues later in the infusion.

5.8.1.3 Inlet configuration – SP1 upwards

The rest of the resin inlets from SP1 upwards were setup with interconnected resin feeds for the inner and outer skin. These feeds were designed to maintain the uniform flow front across the section thickness. The inlets consisted of three parts: a resin feed connected to the injection machine, a length of spiral tube extending across the width of the demonstrator and an open channel within the foam core. These are colour coded in Figure 107. Resin was fed from the injection machine to each inlet via sealed resin feed tubes, shown in yellow in Figure 107. A single length of spiral tube extended across the width of the demonstrator's inner surface to deliver resin directly to the inner skin. The resin feed tubes were connected to the spiral tube at multiple locations to distribute resin evenly across the width and maintain a symmetric and even infusion. A strip of flow mesh was positioned between the laminate and spiral tube to facilitate separation of the inlets from the laminate after cure.

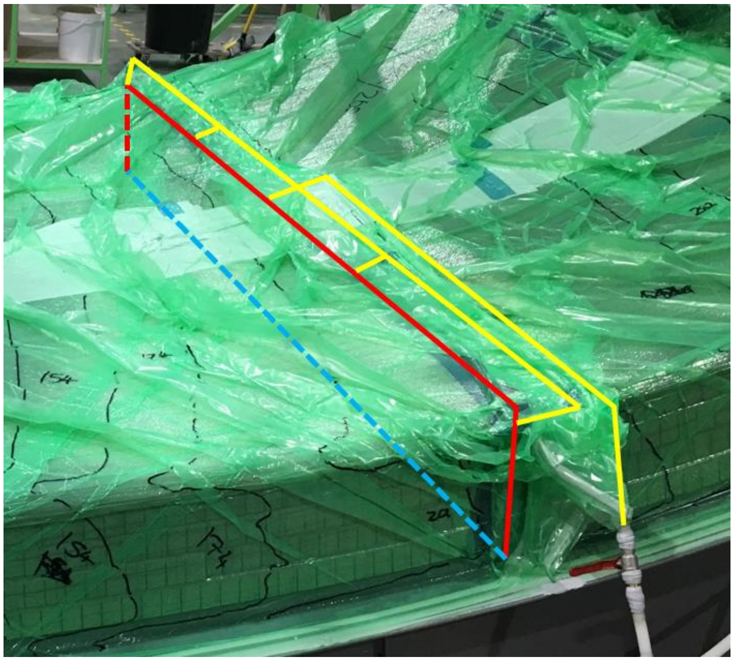


Figure 107: Resin feed for inner and outer skin. Spiral tube (red), resin channel in foam core (blue) and resin feed tubes from injection machine (yellow). Dotted lines represent hidden features.

The spiral tube on the inner skin also extended around the edges of the part to supply resin to the bottom skin. 10x10mm resin channels were cut into the outer surface of the foam core during the layup process as shown by the blue line in Figure 107. These channels are connected to the spiral tubes and deliver resin directly to the outer skin, thus forming a single, interconnected inlet around the cross section of the demonstrator. Cutting channels in the foam core avoids the need for embedded channels in the tool surface.

5.8.1.4 Outlet Configuration

A single vacuum outlet was positioned at the top of the part. The laminate was folded around the top of the tool for stability, with the vacuum outlet positioned on the back of the tool surface, as shown in Figure 108. The outlet consisted of a single piece of spiral tube that was connected to vacuum on either end. A large catch-pot was positioned between the vacuum outlet and vacuum pump.

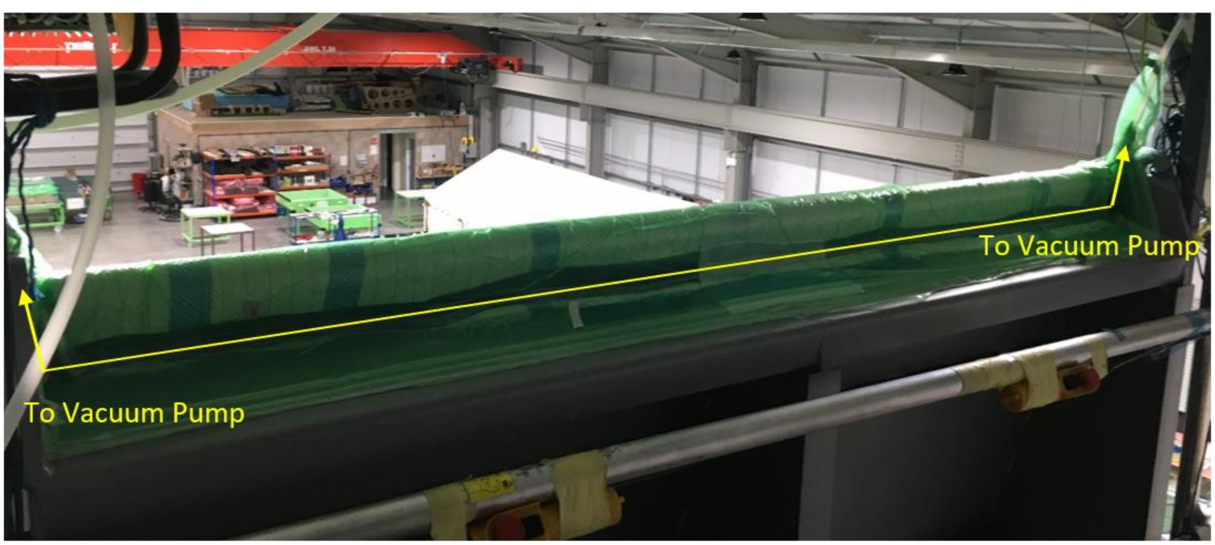


Figure 108: Vacuum outlet (highlighted in yellow) at top of demonstrator, on back side of tool surface

5.8.2 Vacuum Bagging

Two vacuum bags were applied to seal the part to the tool. A primary vacuum bag is used to contain the resin and provide a means to infuse the part. This is contained within a secondary vacuum bag which provides redundancy in case of leaks and a compaction pressure to limit resin drainage at vertical sections. As the infusion progresses local pressures behind the resin flow front approach atmospheric values, and when combined with local hydrostatic pressures can lead to downwards resin drainage and vacuum bag "ballooning". The compaction provided by the secondary bag should limit this ballooning effect.

The primary vacuum bag was applied directly to the tool surface with large pleats at each inlet location along the outer tacky tape perimeter. Two lines of tacky tape were used to seal the vacuum bag against the tool surface to minimise the risk of leaks. This demonstrator was more prone to leaks than previous infusions because of both the high volume of stray glass fibres (mostly from the Saerflow) littering the tool surface perimeter and the limited access to some regions of the tool. Tacky tape was placed on the tool surface prior to layup to reduce the number of stray fibres crossing the tacky tape seal. Despite best efforts to clear any stray fibres prior to bagging, it is inevitable that some fibres remain, potentially compromising the seal between the tacky tape and vacuum bag.

Through-bag connections were avoided in the primary bag as these generally have a greater risk of causing leaks. Pleats (or folds) were made in the vacuum bag to minimise the risk of the bag stretching and to provide lower risk pathways for inlet and outlet tubes to enter and leave the bag. By connecting both inner and outer skin inlets together the total number of tubes entering the bag are halved, further reducing the chance of leaks. A secondary outer bag was applied over the first, sealed against the tool surface perimeter using tacky tape. A central strip of bleeder fabric was placed between the two vacuum bags to help distribute the compaction across the entire surface.

A vacuum drop test was conducted after the part had been left under vacuum for 24 hours. The vacuum level within the inner bag reached -0.972 bar before the test and dropped by 0.01 bar after 30 minutes of being separated from the vacuum pump. This indicated that the primary vacuum bag seal was very good.

5.8.3 Infusion Results

This section discusses infusion parameters recorded during the infusion process to determine the effectiveness of the chosen infusion scheme. These help to inform a subsequent evaluation of the quality of the part and general success of this infusion. Table 37 shows the infusion parameters that were recorded periodically during the process.

Table 37: Measured infusion parameters.

Parameter	Purpose
Ambient temperature	Affects resin viscosity and cure time. Resin viscosity affects speeds of infusion.
Ambient relative humidity	Affects moisture content of fibres and resin, and hence quality of part.
Resin flow front progression across vacuum bag surface where visible	Indicates the speed of resin flow through different sections of the part.
Resin flow rate measured at resin injection machine nozzle	Indicates the volume of resin delivered to different sections of the part.
Total volume of resin delivered from the resin injection machine	Indicates the volume of resin delivered to different sections of the part.
Pressure (positive or negative) supplied by the resin injection machine pump, referred to in this report as "injection pressure"	Injection pressure affects local pressure at flow front, and hence speed of infusion and part consolidation.
Time at which each inlet was opened	Opening of inlets at correct time is crucial for a successful infusion. Affects overall speed and part quality.
Time at which various sections of the structure began to cure/exotherm	Indicates how far ahead the resin flow front is from the cure.

5.8.3.1 Resin Flow Front Progression

Overall, the infusion was a success with all areas of the part appearing to be fully wet out after 17 hours, except for the top 0.5m region. The flow channels and perforations within the foam worked well, evenly distributing resin and creating a uniform flow front across the width and thickness of the part. A total of 962 litres of resin was infused into the part during the process. Figure 109 shows the fully infused demonstrator section immediately after the infusion process had finished.

Figure 109: Fully infused demonstrator (white strip in centre is bleeder fabric between inner and outer bags)

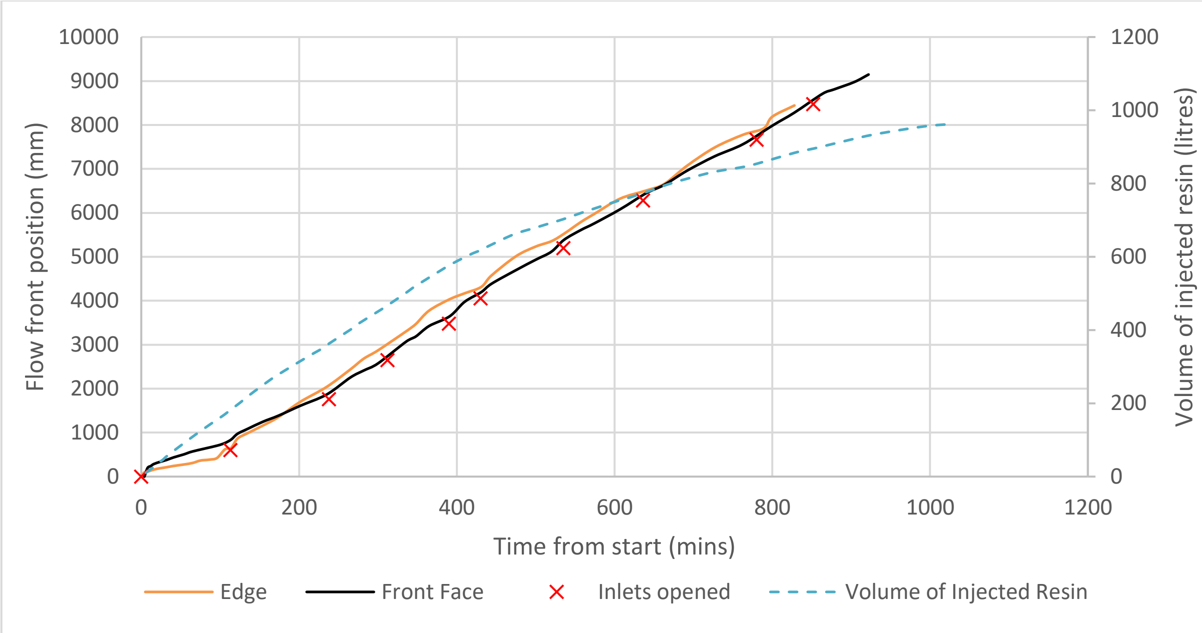


Figure 110: Flow front progression during demonstrator infusion

Figure 110 shows how the flow rate of the resin remained fairly constant throughout the process despite the significant variations in sectional composition (i.e., the different sandwich sectional thicknesses and monolithic joint support details). The only exception to this is the monolithic keel which infused at a slightly slower rate compared to the rest of the demonstrator. This was not seen during the penultimate infusion trial and is thought to be due to limitations on the maximum resin flow rate imposed by the diameter of the infusion tubes.

The red crosses show when each resin inlet was opened. All red crosses are located below the flow front progression lines, indicating that the inlets were opened after the flow front had passed their position. This was purposefully done to avoid any lock-offs near the inlets, which can occur if inlets are opened before the flow front has reached them.

The gradient of the dashed line in Figure 110 shows the rate of resin delivered into the part by the injection machine. As expected, the rate of resin delivered into the part reduces over time as the laminate cross-sectional area reduces further up the part. The reduction in gradient occurs at the opening of inlet 5, which is located at the interface between SP1 and SP2 (i.e., where the sandwich thickness drops significantly).

5.8.3.2 Variation in Ambient Environment

Figure 111 shows the variation in temperature and relative humidity over the course of the infusion. The maximum temperature and humidity changes were 7.5°C and 9% respectively, ranging from 24.1°C and 35% to 16.6°C and 26%. These variations appear to have had minimal impact on the infusion process. Whilst these variations are not as extreme as the maximum expected within a shipyard environment (Temp: 15°C to 35°C, RH: 30% (at 35°C) to 85%), it is a good indication that the process is tolerant to changes in temperature and humidity. It should also be noted that no drastic measures were taken to regulate these variables during the infusion process. Further testing and simulations could be done to understand these effects better, especially concerning the resin cure window relative to infusion speed.

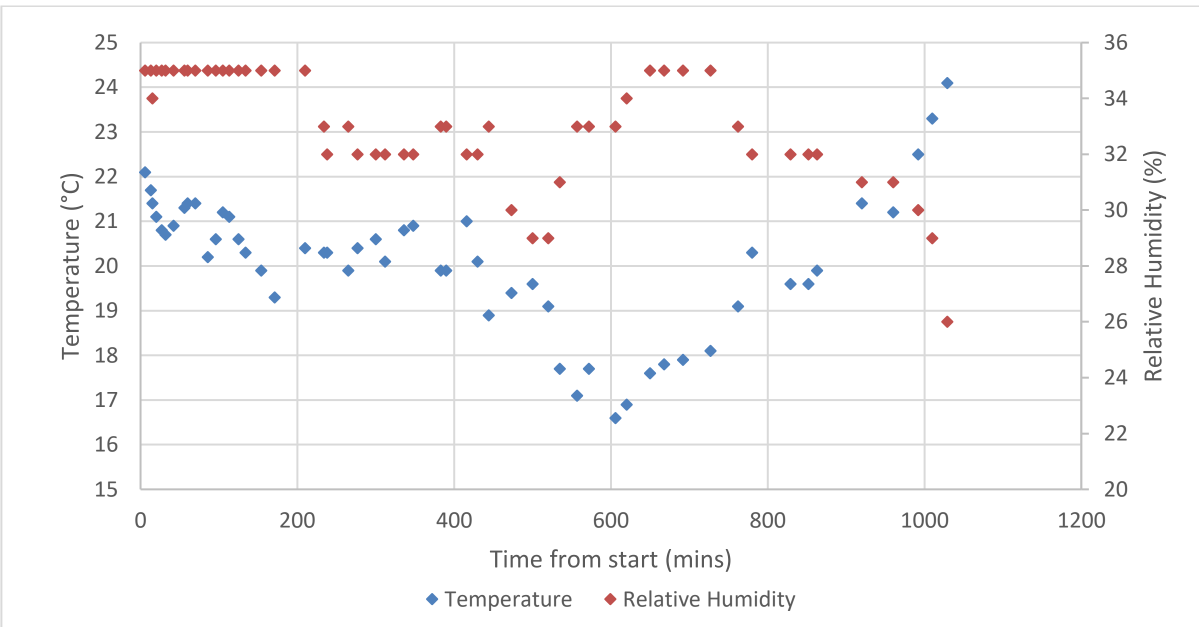
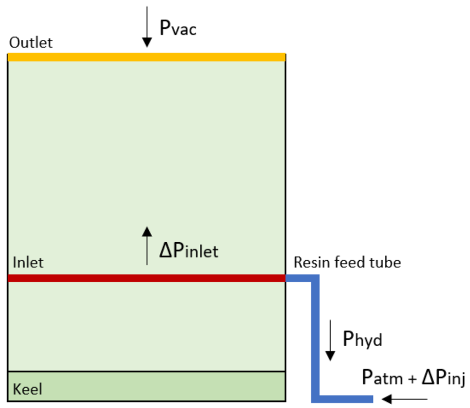


Figure 111: Temperature and humidity variation during demonstrator infusion

5.8.3.3 Injection Pressure

Hydrostatic pressure builds up in the resin feed tube and increases with the height of each resin inlet. This hydrostatic pressure must be overcome to deliver resin to sections of the part raised high off the ground. The applied vacuum pressure is enough to overcome the hydrostatic pressure in this infusion, as demonstrated in previous trials. However, without intervention this reduces the pressure difference that drives the infusion, leading to slower resin flow and potentially poor fibre wet out.

The purpose of applying injection pressure is to counteract the hydrostatic pressure and hence reduce the loss in the pressure difference driving the infusion. Figure 112 shows the main pressures influencing the demonstrator infusion process when a resin inlet is opened.



P_{vac} = Pressure at vacuum outlet

ΔP_{inlet} = Effective pressure difference driving the infusion (at inlet)

P_{hyd} = Maximum hydrostatic pressure in resin feed tube

P_{atm} = Ambient atmospheric pressure

ΔP_{inj} = Additional injection pressure change supplied by injection machine

Figure 112: Simplified diagram showing front view of the demonstrator and the pressures influencing the infusion when a resin inlet is opened

Figure 113 shows the measured and calculated pressure values throughout the infusion process. Pressure sensors were not installed in the demonstrator as these require additional through-bag connections and increase the risk of leaks during the infusion process. Therefore, it was only possible to measure/control the three pressures acting externally: P_{atm}, ΔP_{inj} and P_{vac}. P_{hyd} and ΔP_{inlet} were estimated using Equations (18) and (19):

$$P_{hyd} = \rho_{resin}.\, g.\, h_{inlet} \tag{18}$$

Where ρ_{resin} = density of resin, g = 9.81m/s^2, h_{inlet} = height of the inlet from ground level

$$\Delta P_{inlet} = P_{atm} + \Delta P_{inj} - P_{vac} - P_{hyd} \tag{19}$$

Where P_{atm} = 1 bar, ΔP_{inj} = Set by operator, P_{vac} = 0 bar

Equations (18) and (19) assume the resin feed tube and inlet spiral tubes are fully filled with resin, whilst the laminate above the inlet is completely dry and connected to the vacuum outlet. The purpose of these calculations is to understand how effective the application of injection pressure is for counteracting the hydrostatic pressure at each resin inlet.

Figure 113 displays data for P_{inj}, P_{hyd} and ΔP_{inlet}. P_{atm} and P_{vac} are not displayed on this graph as they are static values (1 and 0 respectively). Instead, $\Delta P_{inlet}(max)$ is shown. This is the maximum pressure difference achievable for a vacuum assisted resin infusion process and is expressed as:

$$\Delta P_{inlet}(max) = P_{atm} - P_{vac} \tag{20}$$

ΔP_{inlet} and $\Delta P_{inlet}(max)$ are expressed as negative values in Figure 113 to indicate suction as opposed to pressurised injection. All values are plotted against time from the start of the infusion. Data is shown up to 922 minutes from the start, at which point the resin had reached the vacuum outlet at 6m.

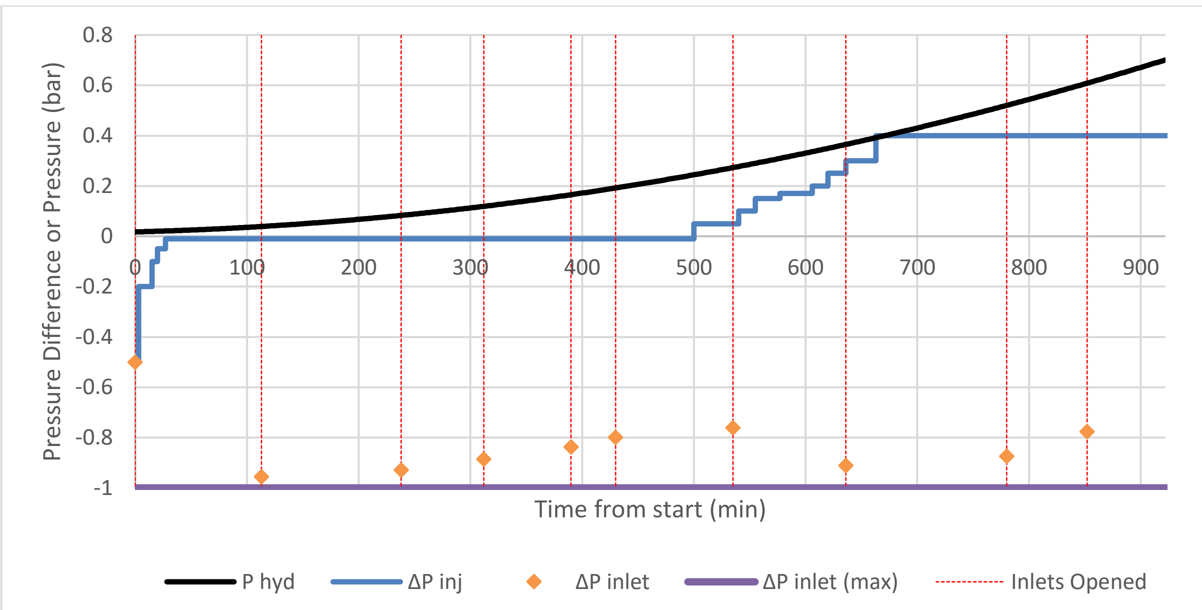


Figure 113: Measured and estimated pressures throughout demonstrator infusion

The maximum hydrostatic pressure in the resin feed tube, P_{hyd}, is shown in Figure 113. As expected, this value increases steadily as the infusion progresses, from 0bar (ground level) to ~0.64bar (6m high). The red vertical lines indicate the opening of inlets. It is the values of P_{hyd} that intersect these red lines which are of interest, as they represent the hydrostatic pressures that must be overcome to deliver resin to each inlet.

The pressure change supplied by the injection machine, ΔP_{inj}, was manually adjusted based upon continual observation of the process. A negative injection pressure was applied at the start of the process to prevent vacuum bag ballooning around the monolithic keel. At 500 minutes the injection pressure was increased incrementally from 0 bar to 0.4 bar to counter the hydrostatic pressure. Care was taken to not supply an injection pressure that would exceed the hydrostatic pressure, as this could lead to a pressure at the inlet greater than 1 bar, resulting in localised resin pooling and vacuum bag ballooning. The injection pressure could not be raised above 0.4bar as the seals in the resin feed tubes at ground level could not withstand greater pressures.

Figure 113 also shows how the application of injection pressure maintained a pressure difference at each inlet, ΔP_{inlet}, of around -1 to -0.8bar. This indicates that the approach was successful. Further work could be done to integrate sensor data into a closed loop control system to automatically supply the correct amount of injection pressure to exactly counter the hydrostatic pressures. This would be a more effective and robust solution than controlling the injection pressure manually.

5.8.3.4 Progressive resin cure

It took 17 hours to fully infuse the demonstrator, much longer than the final infusion trial and exceeding the 8-hour goal. This meant that the infusion time was now more comparable to the cure time of the resin, allowing lower sections to cure whilst upper sections were still being infused. This helped to prevent resin drainage (due to gravity) from laminates and core channels in the upper half of the demonstrator. Figure 114 shows the progression of cure throughout the part, as determined by measuring the surface temperature at intervals (and thus indicating an exothermic reaction was taking place). The "resin exotherm" data points show the time and position at which the preform surface temperature exceeded 50°C. This data acts as an indication of the progression of cure in relation to the resin flow front. It should be noted that the resin cure will have occurred slightly earlier than the recorded exothermic reaction.

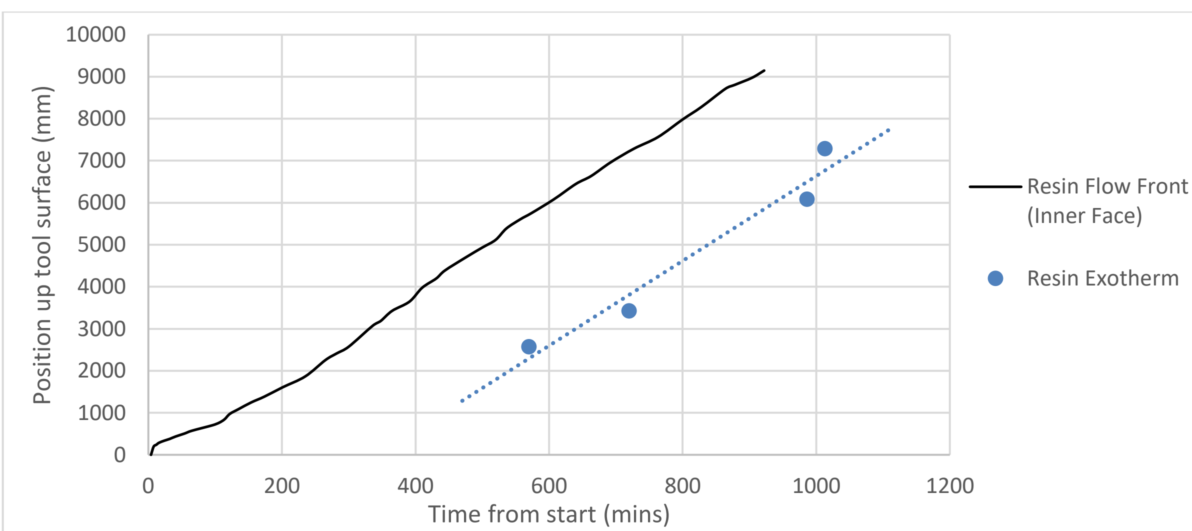


Figure 114: Progressive resin exothermic reaction in relation to flow front progression

Figure 114 shows how the resin cure follows the infusion at a steady rate. By the time the flow front had reached the top of the demonstrator, more than half of the section had cured. This quick cure in relation to infusion time is ideal as it significantly reduces the likelihood of process issues, such as resin drainage or bag leaks, from negatively effecting the quality of the finished part. Further work should be done to optimise the cure time in relation to the infusion progression such that each section begins to cure as soon as it has been fully infused. This may require tighter environmental controls which could undermine the initial goal of providing a robust infusion process usable in a variable shipyard environment.

5.8.3.5 Evaluation of infusion process against requirements

Process requirements were previously outlined in Table 24, Section 3.9. Those directly relevant to the infusion process are used here to evaluate the demonstrator infusion. This evaluation is presented in Table 38.

Table 38: Evaluation of demonstrator infusion against relevant requirements

Requirement	Description	Target Value	Measured Value
Maximum infusion duration	Maximum total duration for resin infusion process (excluding laying, vacuum bagging, and cure).	8 hours	17 hours
Process robustness	Manufacturing process must be able to operate within prescribed range of ambient conditions.	Temp: 15°C to 35°C, RH: 30% (at 35°C) to 85%	Temp: 16.6°C to 24.1°C, RH: 26% to 35%

The demonstrator infusion process did not fully meet the process requirements outlined in Chapter 3. The total infusion duration was significantly longer than a typical 8-hour shift. The author and colleagues monitored and controlled the infusion for the full 17-hour duration. It is important to note the additional setup and post-infusion clean-up time which is not included in this figure. Based upon this experience, it would not be feasible for a single team to monitor an infusion process for this duration in a commercial production environment. Multiple teams would therefore be required to work alternating shifts to conduct an infusion process of this duration. This adds further complexity to the process as information on the infusion procedure (general monitoring/observations, any issues encountered etc…) would need to be transferred between teams mid-way through the process. Furthermore, a longer infusion process increases production cost. An effective solution would therefore be to accelerate the resin infusion process and resin gel time. This is discussed in further detail in Section 5.15.

The infusion process was conducted in a variable factory environment to somewhat simulate a steel shipyard. The temperate and relative humidity range experienced during the infusion process does not fully represent the full range of ambient conditions in a shipyard, however this demonstration does show

how the resin infusion scheme developed in this work is fairly insensitive to these changes. The inlet configuration, use of open resin channels through the preform and injection pressure to counter hydrostatic head enabled a steady infusion rate across the part despite variations in ambient conditions. The full range was not explored in this work as it was considered too risky for a one-off production activity. Further work is suggested to explore the full range of ambient conditions.

Despite not meeting the project requirements, the results of this infusion process show promise. The author believes that further refinements to this process (that are outlined in Section 5.15) will achieve an infusion process that fully meets these requirements.

5.9 Cure/Post Cure

The part was left at room temperature (varying from 11°C to 22°C daily) for two weeks, followed by a post cure of 40°C for 96 hours. Insulation was built around the back of the tooling to create an enclosed air cavity which was heated with dedicated air heaters. An insulation blanket and air heater were used to cover and heat the inner surface of the part.

It is important to note that the majority of the demonstrator experienced a resin cure exotherm greater than 50°C. The post cure is therefore a contingency to ensure all parts of the structure, especially thinner sections towards the top, receive sufficient heating as prescribed by the resin supplier.

5.10 Demoulding

Demoulding such a large structure poses a significant risk to both the structural integrity of the part and the health and safety of all personnel. The four factors that make this demoulding operation particularly dangerous are:

- The weight of the part; estimated at 3.5 tonnes. This puts high strain on lifting equipment and could result in high impact forces if the part is dropped.
- The contact area between the part and tooling is large, requiring a large amount of force to separate the two.
- Curvature of the tool acts like a ramp, potentially propelling the demoulded part across the factory once demoulded.
- The grease effect observed on the surface of the cured resin creates a low friction contact surface between the part and the tool surface once demoulded, increasing the risk of the part sliding down from the tool.

Prior to demoulding, the demonstrator was supported at four points using an overhead 7 tonne gantry crane. Two lifting pins were drilled into each side of the monolithic keel, and a lifting strap was used to support the demonstrator further up the part. Due to the high force required to demould the part, it was deemed unsuitable to use the crane to pull the part from the tool as the high force could damage the part and the lifting equipment. Instead, the part was progressively peeled away from the surface by wedging plastic inserts between the part and the tool. This reduced part flexure and thus risk of damage. After the part was separated from the tool surface it was moved onto a support trolley using the overhead gantry.

5.11 Part Inspection

The vacuum bags and other infusion consumables were removed after the part was demoulded. The top layer of peel ply was left on and would be removed just before bonding of the decks and bulkheads. This ensures a good quality bond surface that is free of contaminants. The part was visually inspected by the author and the quality of the part was evaluated against the requirements and defect criteria outlined in Section 3.9. Table 40 presents a summary of the evaluation against the defect acceptance criteria. Any non-conformities are discussed later in this section. The relevance and suitability of these criteria, and how they could relate to a 75m hull shell is also discussed. Revised criteria are presented at the end of this section based upon the findings. Table 39 presents a summary of the evaluation of the demonstrator quality against the relevant project requirements. Only requirements directly related to part quality are included. Requirements relating to the manufacturing process are discussed in Sections 5.7 and 5.8.

The summaries presented in Table 39 and Table 40 indicate that the overall quality of the demonstrator section was good, with most of the defect criteria and requirements having been met. Criteria highlighted in red indicate non-conformance, whilst yellow indicates partial compliance of that the result could not be verified due to difficulties taking measurements. Green indicates that the criteria have been met. The key instances of non-conformance are the large dry region, presence of metallic pins, and two large wrinkles in the inner skin.

Table 39: Evaluation of demonstrator quality against relevant project requirements

Requirement	Description	Target Value	Measured Value
Laminate fibre weight fraction	Applied to all structural laminates within the demonstrator.	65% - 72%	68.3% Average.
Surface accuracy	Geometry of inner and outer surfaces of the demonstrator must not vary from the design schematic by an amount greater than the stated value.	+/-5mm	Part geometry appears to match design within +/-5mm in most regions, but difficult to confirm.

Table 40: Evaluation of demonstrator quality against defect acceptance criteria

Defect	Level of acceptance	Definition of acceptance level	Evaluation of Demonstrator
Chip	3	Small piece broken off an edge or surface. **Max. dimension: 6.5mm.**	No defect detected.
Crack	1	Separation of the laminate, visible on opposite surfaces, extending through the laminate. **None.**	No defect detected.
Crack, surface	3	Crack on laminate surface only. **Max length: 6.5mm.**	No defect detected.
Crazing	2	Fire cracks at or under laminate surface. **Max. dimension: 13mm.**	No defect detected.
Delamination, edge	3	Separation of material layers at edge of laminate. **Max. dimension: 6.5mm.**	No defect detected.
Delamination, internal	1	Separation of material layers within laminate. **None.**	No defect detected.
Dry-spot	2	Area where reinforcement has not been wetted with resin. **Max. diameter: 9.5mm.**	Large dry region spanning the top 500mm of the demonstrator. Defect exceeds allowable criteria.
Foreign inclusion (metallic)	1	Metallic particles within laminate that are foreign to its composition. **None.**	Metallic lifting pins remained within monolithic joint 1 insert. Defect exceeds allowable criteria.
Foreign inclusion (non-metallic)	3	Non-metallic particles within laminate that are foreign to its composition. **Max. dimension: 1.5mm.**	No defect detected.
Fracture	1	Rupture of laminate surface without complete penetration. **None.**	No defect detected.
Air bubble (void)	3	Air entrapment within laminate. **Max. diameter: 3mm.**	No voidage detected within quadaxial reinforcement plies. Bubbles detected within top layer of Saerflow only. Maximum bubble diameter less than 3mm, however frequency of bubbles exceeds acceptable limit.
Blister	1	Rounded elevation on laminate surface. **None.**	No defect detected.
Burned	1	Discoloration, distortion, or destruction of laminate surface due to thermal degradation. **None.**	No defect detected.
Pimple	3	Small, sharp, conical elevation on surface of laminate. **Max. diameter: 3mm.**	No defect detected.
Pit (pinhole)	3	Small crater in laminate surface. **Max. diameter: 0.8mm, depth <20% laminate thickness.**	No defect detected.
Porosity (pinhole)	3	Presence of numerous visible pits. **Max. 50 per unit area for acceptance level 3.**	No defect detected.
Pre-gel	3	Unintentional additional layer of cured resin over laminate. **Max. dimension: 13mm, height within surface tolerance.**	Two volumes of resin (length: 300mm and 1000mm, max. depth: 30mm) can be seen on the surface of the inner skin laminate. Less severe regions can be classified as pre-gel, whilst more pronounced volumes are classified as resin pockets. These defects exceed both allowable criteria, although they may be removed to achieve compliance. Internal resin pockets cannot be detected via visual inspection (see later discussion).
Resin-pocket	3	Accumulation of excess resin in a localised area. **Max. diameter: 6.5mm.**	
Resin-rich edge	3	Insufficient reinforcement at edge of laminate. **Max: 0.8mm from edge.**	Cannot confirm acceptance, see later discussion.
Shrink-mark	3	Depression on surface of laminate. **Max. diameter: 14mm, depth <25% laminate thickness.**	No defect detected.
Wrinkles	3	Waviness in reinforcement material within laminate. **Max. dimension: 25mm, depth >15% laminate thickness.**	Two large wrinkles within the inner skin at joint 1 and joint 2 transitions. The defect areas are approximately 30mm in length, 10mm in depth, and span the full width of the part. Defect exceeds allowable criteria.

5.11.1 Dry-spots

Figure 115 shows the infused hull shell prior to finishing. A large dry region is observed over the top 500mm of the part that spans the entire demonstrator width. This far exceeds the maximum allowable dry spot size defined in the defect acceptance criteria. The reinforcement in this region appeared semi-wet out with resin during inspection, indicating that this region was infused with resin at one point. This coincides with the observations seen during the infusion process, where the entire preform was shown to be fully infused with resin. The plies can be separated from one-another and the laminate pulled apart by hand. It is clear that this section is not fit for purpose and cannot support the intended design loads. This evaluation criterion seems mostly reasonable and achievable. Non-conformance in this case is due to processing issues. It should be noted that this evaluation criterion can only be used alongside visual inspection to evaluate the quality of the outermost regions of the structural laminates. It is not possible to detect dry spots deep within the thick monolithic and sandwich sections using visual inspection. A bright light source can be used to shine light down into the laminate surface to aid visual inspection, however one can only see down to the first few plies using this approach. This evaluation criterion (as with many other discussed in this section) should therefore be used with caution when determining the overall quality of the structure. This reinforces the importance of a robust and predictable infusion.

The cause of this dry spot is believed to be resin drainage. It appears that, despite the closer match between the infusion duration and resin cure time, the resin had once again drained down from the top section (as witnessed during the final infusion trial) sometime between the end of the infusion and cure of the resin; however, the resin drainage was caused by a different issue in the demonstrator infusion. Apart from the very top of the part, the demonstrator appears to be fully wet-out with resin, including the slits and channels within the foam core.

Figure 115: Cured and demoulded demonstrator

During the final infusion trial (Section 4.8) the majority of the resin within the preform remained in a liquid state for some hours after the infusion had completed, allowing the resin to drain downwards through the preform despite vacuum being applied. In the demonstrator infusion the resin cure time and infusion duration were more closely matched, allowing the majority of the resin within preform to cure by the time the infusion had completed, as shown in Figure 114. Only the top 2 metres of the preform contained liquid resin when the demonstrator infusion had finished. The resin in this region was unable to drain down into lower parts of the structure like it had done in the final infusion trial. Instead, this resin drained over the surface of the cured preform and collected further down the part in two large pools underneath the vacuum bag as shown in Figure 117C and D (these defects are discussed in the next section). The applied vacuum should have prevented this from happening; however, vacuum within the bag was lost sometime overnight between the end of the infusion and the cure of the top volume of resin. This issue with the vacuum bag therefore caused the dry region at the top of the demonstrator.

For the bag to have lost vacuum there must have been small leaks present. Given the size of the bag and poor accessibility in some areas, this is not entirely surprising. However, even with these leaks the vacuum level within the outer bag should have remained constant as it was directly connected to the vacuum pump.

Figure 116: Inner and outer vacuum bags welded together (photo taken after demoulding to highlight welding effect)

For the outer vacuum bag to have lost compaction, it must have been disconnected from the vacuum pump. Upon further inspection it was found that the inner and outer vacuum bags had welded together around several resin inlets, creating sealed cavities between the two bags that were disconnected from the vacuum pump. With no vacuum pump acting on these areas, it was inevitable that the vacuum would be lost over time due to the small leaks previously mentioned. It is currently not understood why the vacuum bags had welded together as the exotherm temperatures were well below the operational limits of the bag. The proximity of these welds to the resin inlets suggests that small quantities of resin may have somehow penetrated between the two vacuum bags, welding the bags closed as it cured. However, no obvious signs of resin were observed between the vacuum bags, and so further research is required to understand why the vacuum bags had welded together in this way.

The results of further investigations into this welding effect could be implemented into the next iteration of this process to prevent the dry region forming. In the meantime, two suggestions are proposed to reduce the risk of the upper dry region forming due to vacuum losses in the bag:

1. Implementing more vacuum ports across the preform to reduce the chance of vacuum lock-offs forming if the bags weld together.
2. Shortening the cure time for resin that is injected into the final two metres of the preform, reducing the window of time that resin can drain downwards.

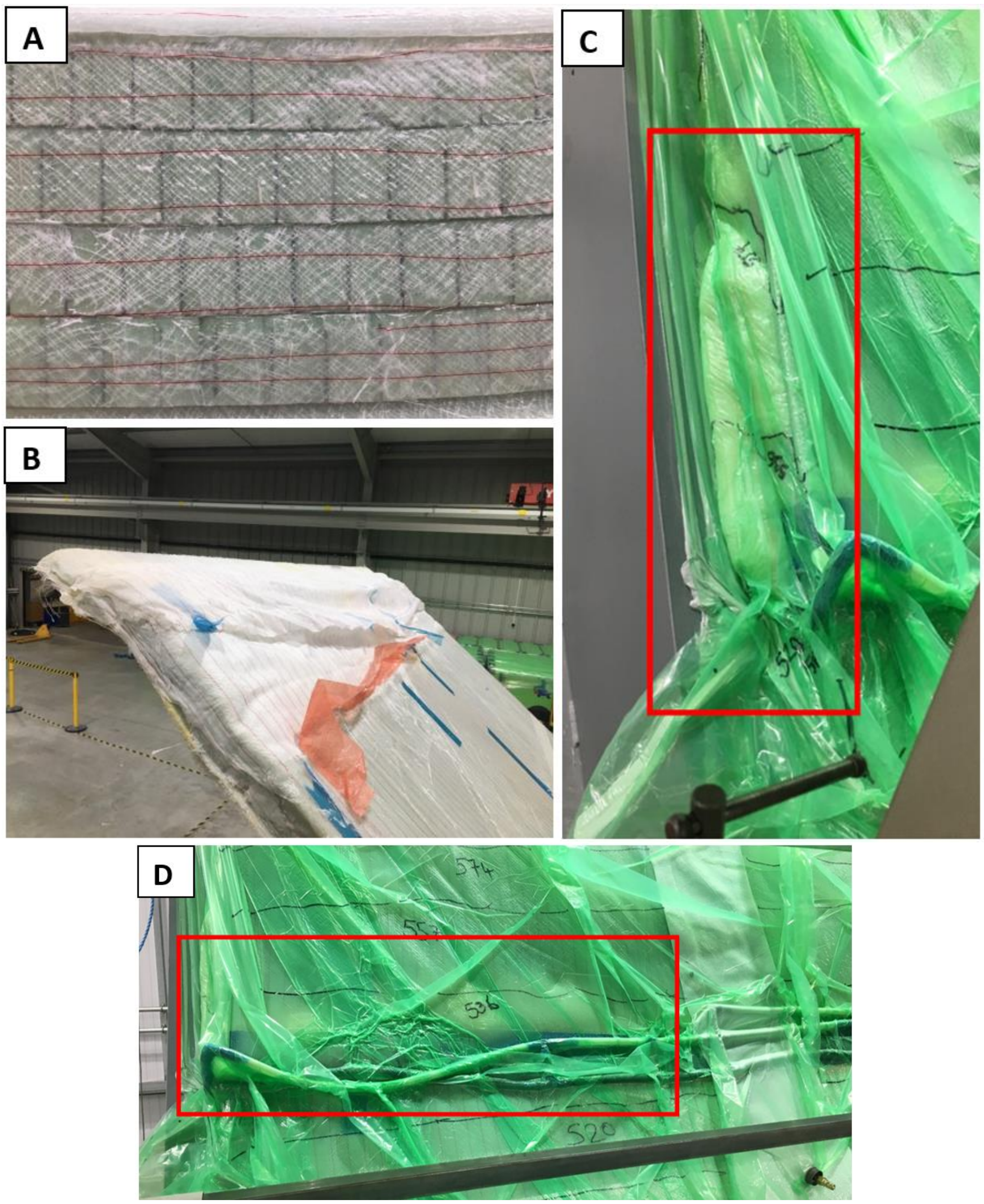


Figure 117: A: Foam core infused with resin, B: Dry region at top of demonstrator, C & D: Evidence of resin drainage near inlet 8.

5.11.2 Pre-gel and resin pockets

Two volumes of cured resin were identified on the surface of the demonstrator section and are shown in Figure 117C and D. As discussed previously, these defects have formed due to resin drainage shortly after the resin infusion process. The largest volume of cured resin is shown in Figure 117D and is located over the inner skin towards the top of the demonstrator. The reader may have noticed that this defect is not present in Figure 115. The placement of peel ply over the entire inner surface of the preform meant that this volume of cured resin could be easily removed from the laminate during the debagging procedure. This defect is therefore not a concern.

The other volume of resin is located on the side face of the demonstrator and is shown in Figure 117C. Removal of this defect is more challenging as no peel ply was located here. The presence of this defect is therefore the primary cause of non-compliance for this acceptance criterion. However, it is important to consider the relevance of the position of this defect with regards to the 75m hull shell. This open side face would not exist on a continuous 75m hull shell, and so this type of defect would not be able to form here. Assuming that peel ply is positioned over the entire surface (which may be costly), any resin pockets or pre-gel could be removed during the finishing stage to achieve compliance.

The formation of linear grooves within thick monolithic laminates due to the gaps between splice joints was highlighted in Section 5.7. The author identified the presence of these grooves in both the monolithic keel preform and pre-cured joint 1 monolithic insert. If left unfilled, these gaps could result in linear resin pockets which exceed the defect acceptance criteria. It is not known whether vacuum compaction caused the inner skin reinforcement to fill these grooves. The thickness of the laminate meant that it was not possible to see deep enough to confirm this, even with a powerful light source. Therefore, the presence of resin pockets in laminates deep within the structure cannot be confirmed via visual inspection, limiting the usefulness of this defect acceptance criterion. The most effective solution to this issue would be to revise the ply splice joint pattern such that they do not align. The presence of the linear grooves indicates that resin pockets do not form in the gaps between ply splice joints within the laminate skins, and instead result in surface geometry defects which are discussed later in this section.

5.11.3 Foreign inclusion

As discussed in Section 5.8, four metallic lifting pins were left in the monolithic joint 1 insert because they could not be removed without causing damage to the laminate. These features cannot be detected via visual inspection after the demonstrator has been infused as they are located deep within the thickness of the part. Intermediate visual inspection stages for each structural detail were therefore required to identify these defects prior to completion of the hull shell preform. No other metallic foreign objects were detected during the manufacturing procedure or final inspection of the part.

No non-metallic foreign inclusions were identified during the final inspection. However, based upon the author's experience of laying up the glass reinforcement, it is possible that some small pieces (>10mm) of backing film remained within the laminate. Backing film was removed from every ply (and recorded as part of the layup procedure), however the large size of the plies, the method used to cut the rolls, the manual approach of removing the backing film over difficult-to-reach areas, and the limited visibility to the underside of the ply once in position over the tool meant that small fragments of backing film sometimes remained along the edges of the plies. The author identified and removed these fragments during the layup procedure; however, it is possible that some were missed remain in the part. These foreign inclusions would exceed the maximum acceptable dimension (1.5mm), but will not be detectable via visual inspection (unless located near the laminate surface). Given the scale of the process and limited visibility during layup, detecting these defects via visual inspection does not seem like a sensible or efficient solution. Instead, it is proposed that an alternative cutting approach be used to achieve a clean cut along the edges of the reinforcement plies (or simply not cutting the rolls at all), thereby reducing the chance of these backing-film fragments forming and being incorporated into the final part.

5.11.4 Voidage

Another issue observed during the infusion was that of small bubbles appearing within the resin, possibly due to the heavy mixing of the resin and/or small leaks in the inlet pipework. Some of these bubbles remained in the part as the resin cured and are mostly concentrated around the keel and SP1 sections. These bubbles are only visible in the top layer of Saerflow on the inner face. No bubbles can be seen deeper within the laminate or on the outer surface of the demonstrator. This suggests that these bubbles remained within the top Saerflow layer due to its proximity to the resin inlets and greater permeability compared to the quadaxial material.

These bubbles are approximately 1mm in diameter and on average 10 bubbles are present within a 20mm^2 area for the worst affected regions around the keel. The inner surface voidage fraction was estimated at 3.7% in this region using a visual estimation of the 2D bubble-to-laminate area ratio. These bubbles are smaller than the maximum acceptable diameter of 3mm. However, the frequency of these bubbles exceeds the acceptable limit of "no more than 2 defects within 5 inches, and no defect areas within 1 inch of each other”. Inspection of these voids with a bright light found that these bubbles only appear to be present in the top layer of Saerflow, and so are not thought to pose any significant risk to the structural integrity of the part. Failure to fully meet the defect acceptance criteria in this case is therefore not considered to be a critical concern. It appears that a similar, yet less severe voidage issue is occurring in this part to that observed in previous large monolithic infusions (Section 4.7). Implementation of the proposed degassing procedure outlined in Section 4.7 may help to reduce the level of voidage seen in this Saerflow layer.

As discussed for the previous defects, detecting voidage deep within the thick monolithic and sandwich sections via visual inspection is not possible. Suitable process control techniques should therefore be applied to limit the formation of bubbles, such as vacuum bag leak tests and resin degassing procedures.

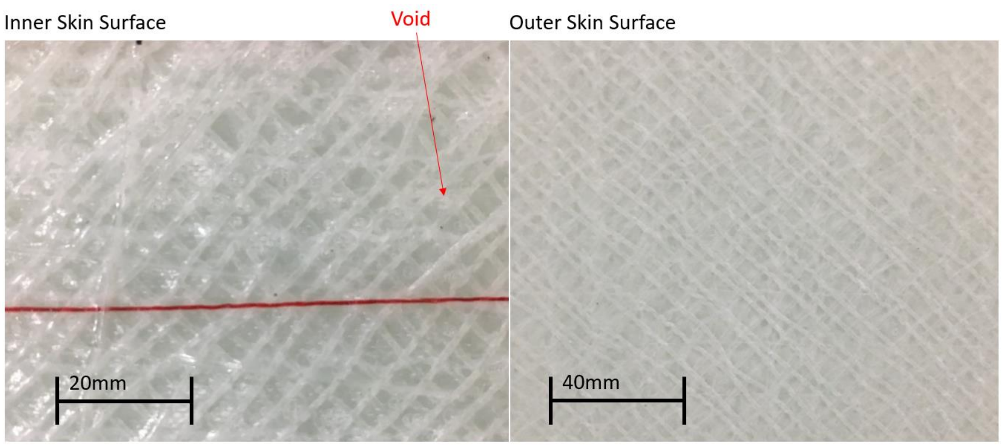


Figure 118: Inner surface (left) and outer surface (right) of the demonstrator keel.

5.11.5 Resin-rich edge

This defect acceptance criterion does not appear to be entirely suitable for this application. The criterion states “Insufficient reinforcement at edge of laminate” but does not provide a criterion for determining what is “Insufficient”. If one is to assume that an insufficient level of reinforcement is one which reduces the fibre weight fraction below the acceptable range, then such a criterion cannot be realistically evaluated in a shipyard environment. This is because the fibre volume fraction is calculated based on sectional thickness and the total number of plies. A lack of reinforcement indicates missing plies at the edge of the part, so the actual number of plies is unknown (depending on visibility, accessibility, and quality of the laminate edge, it may be possible to count them using high resolution photographs, but this may be inaccurate and likely very time consuming for a 75m hull shell). Calculation of fibre weight fraction at this resolution is therefore difficult and impractical for this case study.

To further increase the impracticalities of this criterion, the maximum acceptable range is defined as 0.8mm from the edge of the laminate. This is the highest acceptable range provided for this criterion in ASTM D2563 (ASTM, 1998) (excluding custom criterion). Measuring distances less than 1mm over a 75m long, 6m high curved structure in a shipyard environment does not seem practical. Furthermore, based on the discussions in this thesis regarding realistic ply positional tolerances, a 0.8mm resin rich edge would likely have less impact on structural performance than a 10mm gap between plies. It should also be noted that the full 75m hull shell only has one edge along the gunwale where this acceptance criterion could be applied. It is therefore suggested that this criterion be removed entirely. Meeting the requirements for surface geometry and laminate fibre volume fraction should be sufficient for preventing any notable resin rich edges in this application.

5.11.6 Wrinkles

Two large wrinkles have been identified on the surface of the inner skin at the joint 1 and joint 2 structural transitions and are both shown in Figure 121. These wrinkles are approximately 30mm in length and 10mm in depth and span the entire width of the demonstrator section. The length exceeds the 25mm maximum, whilst the acceptable depth depends on what the engineer considers to be the laminate thickness (the acceptable depth is less than 15% laminate thickness). If one considers the laminate thickness to be the local skin thickness (which seems sensible, as this is where the wrinkle actually forms) then the acceptable maximum wrinkle depths are 3.5mm and 2mm for joint 1 and 2 respectively. The identified wrinkles far exceed these limits.

However, if one considered the laminate thickness at joint 1 to be the total monolithic laminate thickness, then the maximum acceptable wrinkle depth is 37.5mm according to this criterion. This seems excessive for an acceptable defect and indicates that this criterion may not be suitable for thick sections, but rather for thin laminates more commonly used in aerospace applications. If thick monolithic laminates are to be more commonly used in large marine applications, it may be appropriate to devise a new wrinkle acceptance criterion based upon experimental trials and laminate analysis.

These defects formed during the layup procedure due to the sharp transition in geometry and the high bulk factor of the inner skin laminate. Poor accessibility to this region combined with difficulty handling large plies and the limited effectiveness of periodic debulking meant that this wrinkle was difficult to prevent. Improved accessibility and layup techniques could have reduced its size, but the sudden geometric transition is the primary cause. To avoid this wrinkle, it is suggested that the local structure be redesigned with a more gradual transition in thickness.

5.11.7 Surface accuracy

Measurement of surface accuracy was also quite difficult to do using equipment and resources available in a shipyard environment. The sectional thickness of the part was measured manually along both edges of the demonstrator and compared against the desired total sectional thickness values presented in Table 22 in Chapter 3. Figure 119 displays the measured sectional thickness across the entire part. This was a suitable approach for measuring the sectional thickness of this demonstrator. However, this method cannot be used for a 75m hull shell that has no "open edges". An alternative method is explored later in this section that may be more appropriate for a full hull shell.

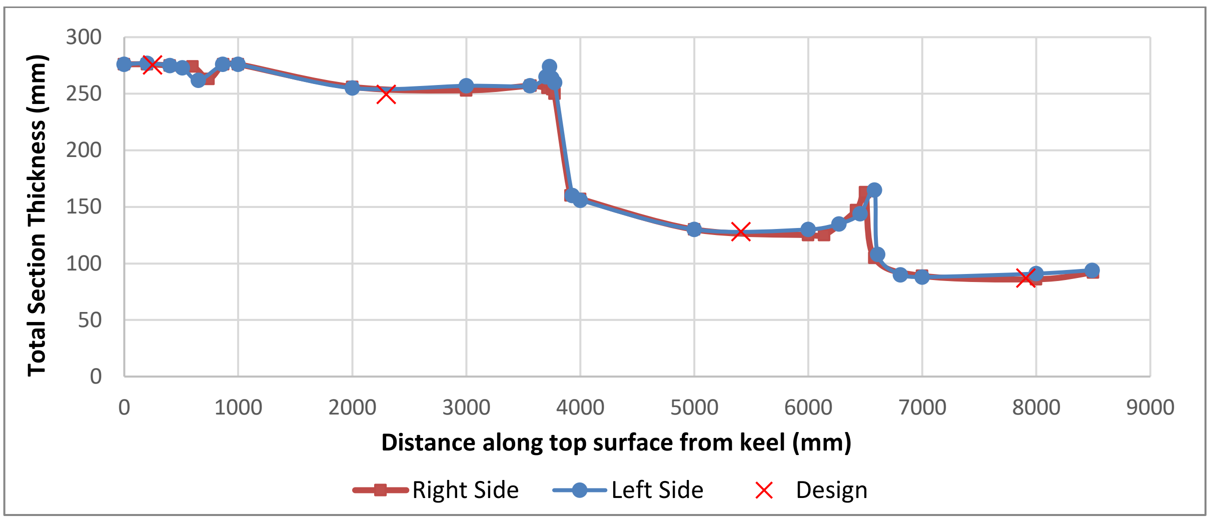


Figure 119: Thickness measurement of demonstrator

Figure 119 shows how the sectional thicknesses of the left and right sides match closely, indicating that the part is geometrically level and uniform. Overall, the measured thicknesses match the desired design thicknesses within the desired +/-5mm tolerance, with the exception of region approximately 700mm from the keel edge. This dip in thickness is located at the keel/SP1 interface and represents a 10mm change in thickness spread over a 350mm distance. Figure 121 shows this slight reduction in thickness on the demonstrator, which appears to be primarily caused by a slight mismatch between the monolithic and foam core taper. This may have been caused by incorrect positioning of the monolithic preforms. The monolithic plies were all positioned within a +/-10mm tolerance as discussed in Section 5.7. However, there may have been some movement in these plies as the upper preform was constructed and the vacuum bag applied.

The gradual reductions in thickness displayed in Figure 119 from 1000mm to 3700mm and 4000mm to 6000mm are expected as these are result of the ply drops featured in the design. The sudden reductions in thickness at 3700mm and 6500mm represent the intended structural transitions at joints 1 and 2 respectively. The increase in thickness at 6000mm to 6500mm represents the joint 2 monolithic ledge. The difference between the red and blue lines locally in this region indicates that this ledge is not level, with the right side approximately 80mm lower than the left side. This feature is therefore deemed unacceptable as it does not lie within the +/-5mm surface tolerance. This misalignment is a result of the practical issues of forming this monolithic feature on the near-vertical tool surface that were previously discussed in Section 5.7. The most effective solution would be to remove this monolithic detail entirely.

A second method was used to quantify the surface accuracy of the demonstrator that did not require access to “open edges”, and thus is more compatible with a 75m hull shell. A laser scan was used to generate a 3D digital image of the demonstrator. This required technologies not typically found in a composites factory or shipyard, however it is possible to outsource this service if required. Figure 120 shows the digital image generated using this method, which can be compared against design geometries to quantify any deviations. The coloured regions in Figure 120 represent the manufactured demonstrator which is compared against an old design geometry in grey. Due to the rapid development approach, a revised CAD model was not generated to represent the final demonstrator design. The numerical values in this image should be ignored as they represent how the demonstrator varies from this old design. Furthermore, the difference in curvature between the design and demonstrator in the side view is due differences between the initial design and the tool geometry. This is a result of the tool surface being shaped to accommodate potential spring-back of the demonstrator due to resin shrinkage. It appears that the predicted geometric shrinkage was over-estimated as there appears to be very little spring-back in the demonstrator. Slight modifications to the tool surface geometry are required to fix this issue in the next iteration of the manufacturing process’ development.

Figure 120 shows how the demonstrator surface is uniform across the width within +/--5mm (excluding areas where defects are present). Combined with the data gathered by the author in Figure 119, it appears that the demonstrator geometry is mostly accurate to within +/-5mm of the final design. The author included the results of this laser scan within this report to highlight the potential of this approach for determining the surface accuracy for the 75m hull shell as an alternative to the manual method of measuring sectional thicknesses.

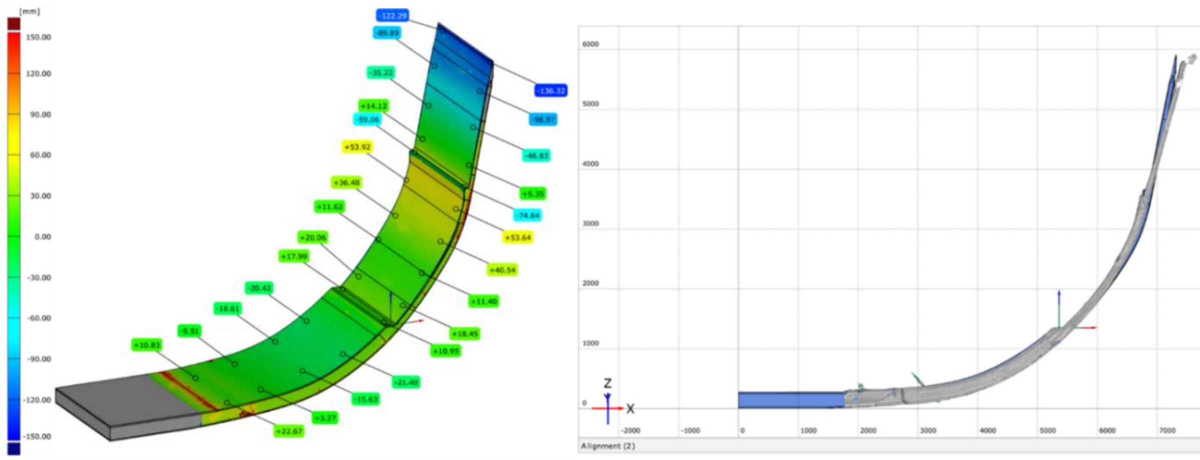


Figure 120: Laser scan results for demonstrator. Left: Variation of inner surface with respect to CAD model. Right: Side view comparing manufactured part with CAD model

Figure 121 also shows the general quality of the structural details within the demonstrator. The joint 1 support ledge appears to be straight and level across the width of the part, providing adequate support for the lower deck. There are no significant changes in thickness at the interfaces between sandwich panel and monolithic, and the shear ties at the joint 2 support are shown to be fully infused with resin.

Figure 121 highlights a potential defect which does not feature within the defect acceptance criteria; fibre bridging at the joint 1 and joint 2 steps. A radius of curvature can be seen over the inner transition angle at these transition regions, indicating some level of fibre bridging. It is likely that this bridging has resulted from the large wrinkles that have formed nearby. It is suggested that an appropriate acceptable fibre bridging value be determined for this case study based upon structural analysis. Judging by the part geometry and access to this feature, it may be appropriate to define an acceptable radius of curvature or a maximum deviation from the design geometry that could be measured manually or by laser scanner.

Figure 122 shows longitudinal grooves that span the entire length of the demonstrator. These are the same type of defect that was observed in Section 5.7, and are the result of the gaps between plies at splice joints within the inner skin laminate. The local reduction in thickness is approximately 5mm. Modifying the layup pattern appears to be the most effective solution to preventing these defects. Similar grooves can also be seen in Figure 121 that span the width of the demonstrator. These are also approximately 5mm in depth but are unrelated to the preform layup. The spiral tubes used for the resin inlets have created these grooves. Alternative inlet tubes or additional layers of flow mesh between the spiral tube and preform may reduce the depth of these grooves in future manufacturing iterations. Figure 122 also provides a comparison of the dry region at the top of the demonstrator on the inner and outer skins. The dry area on the outer skin is much smaller than on the inner skin, suggesting that the majority of the resin drainage occurred between the bag and the inner skin of the part. Finally, several white marks can be seen over the inner surface in Figure 122 and Figure 121. These are where the peel ply has been locally separated from the laminate underneath. Peel ply does not saturate with resin and therefore appears white when separated from the laminate. These marks are not indicative of any surface defects.

5.11.8 Fibre weight fraction

The sectional thickness measurements presented in Figure 119 were used to calculate average fibre weight fraction values across the demonstrator using the methodology outlined in Section 4.2.1. Table 41 displays these values. The maximum and minimum thickness values are used to show the range of fibre weight fractions over each section of the demonstrator.

Table 41: Calculated fibre weight fractions of the demonstrator

Section	Max/Min	Total Sectional Thickness (mm)	Laminate Thickness (mm)	Fibre weight fraction (%)
Keel	Max thickness	276	276	70.6
	Min thickness	262	262	72.9
SP1	Max thickness	276	73	70.8
	Min thickness	255	52	65.3
Joint 1 Monolithic	Max thickness	257	257	69.0
	Min thickness	156	156	68.0
SP2	Max thickness	156	55	63.0
	Min thickness	125	24	70.3
SP3	Max thickness	108	48	48.7
	Min thickness	88	28	63.9
			Average	**68.3**

Overall, the fibre weight fraction of the demonstrator section lies within the acceptable range of 65%-72%, with the average across all sections being 68.3%. Two localised regions in SP2 and SP3 have fibre weight fractions below the acceptable range. These regions of maximum thickness in SP2 and SP3 correspond to localised fibre bridging at joint 1 and 2 respectively, which were discussed previously. Because these are small, localised defects, these fibre weight fraction values have been omitted from the average fibre weight fraction calculation (including these values results in an unrepresentative average fibre weight fraction of 66.3%).

5.11.9 Review of defect acceptance criteria

The visual inspection and measurement of the demonstrator has shown that the overall quality of the part is sufficient, with most requirements and defect acceptance criteria being met. In most cases of non-conformance, it is thought that modifications to the manufacturing process and/or hull shell design will prevent these defects from forming. However, this activity has also highlighted some potential refinements that could be made to the defect acceptance criteria so that the inspection procedure is more relevant to this specific case study.

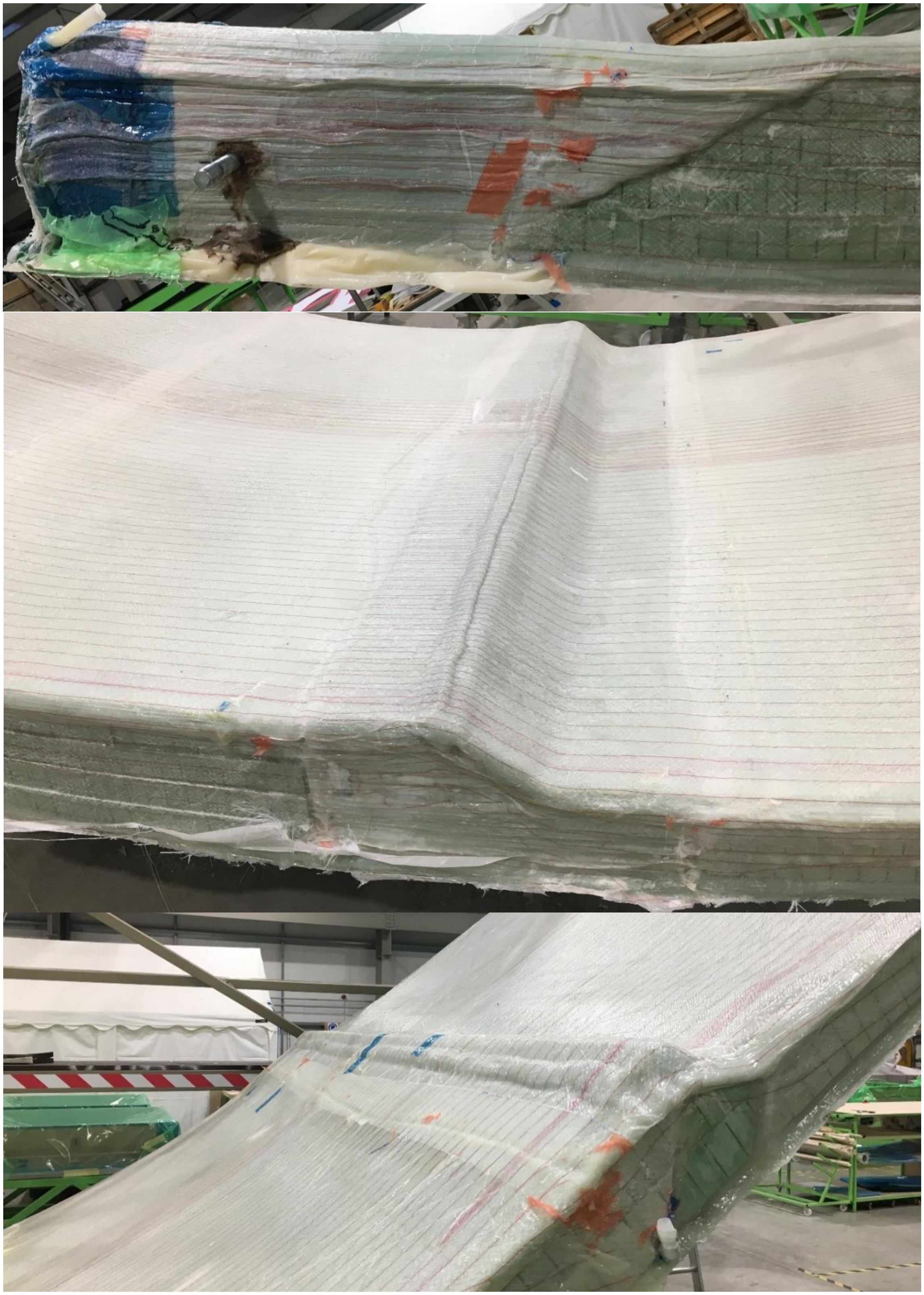


Figure 121: Top: Keel/SP1 interface, Middle: Joint 1 support, Bottom: Joint 2 support.

Figure 122: Demoulded Demonstrator. Top: Demonstrator inner skin (with grooves highlighted), Bottom: Outer skin

A suitable fibre bridging acceptance criterion should be defined for this case study based upon structural analysis and experimental testing. Definition of an acceptable radius of curvature or maximum deviation from the design geometry may be an appropriate measure to evaluate the demonstrator geometry, based upon suitable measurement techniques that can be applied within a shipyard.

The evaluation criterion for resin-rich edges should be removed from the defect acceptance criteria list. This defect definition is vague, and the acceptable dimensions are too small to practically measure in a shipyard environment. Furthermore, the hull shell only has one edge along the gunwale, the quality of which should be adequately controlled via the other acceptance criteria.

The wrinkle acceptance criterion seems unsuitable for thick monolithic laminates (~250mm) as it allows for fairly substantial wrinkles (~25 to 40mm depth for level 2 and 3 acceptance in ASTM D 2563). If thick monolithic laminates become more commonly used in large marine structures, a more suitable defect acceptance criteria should be identified based upon experimental testing and laminate analysis.

This inspection procedure has also identified the key issue of visual inspection for thick composite sections; it is not possible to determine the quality of the structure beneath the visible surface. Intermediate inspection stages throughout the manufacture have been used in this study to identify potential defects which would have otherwise gone undetected. Scheduled inspection throughout the manufacturing process is therefore strongly recommended. Suitable process control procedures may be difficult to implement in practice due to the scale of the part, the numerous production challenges that have been identified and the heavy reliance on manual manufacturing approaches used throughout this manufacturing study. There is no practical method for detecting defects deep within thick monolithic laminates that may form during the infusion process (such as voids). This further highlights the importance of a robust infusion strategy. Implementation of accurate and repeatable automated manufacturing technologies may be one approach to improve process control, repeatability, and part quality.

The criteria that were successfully met in this manufacturing study are assumed to be sufficient from a manufacturing perspective and are therefore not discussed any further in this report. This study has demonstrated what is possible in a shipyard environment with typical composites manufacturing equipment and resources. It is assumed that further refinements to this manufacturing process and its application to a 75m hull shell will also be able to meet these same criteria. Further refinement of these criteria (and perhaps the implementation of even stricter acceptance criteria) should be included in the next design iteration of this structure. This could be done by investigating the effects of various acceptable defects on the mechanical performance of test laminates and representative sections. A combination of experimental tests, laminate analysis, process modelling, and even durability predictions from Chapter 2 could be used to identify a list of acceptable defects that is directly relevant to this specific case study and manufacturing procedure. Determination of an acceptance criteria in this way would no doubt be far more time-consuming and expensive than the approach taken in this study. However, this type of approach could lead to more efficient, longer lasting, and lower cost composite structures in the future.

5.12 Finishing

There was very little finishing work to be done other than repairing the dry region at the top of the demonstrator. To do this, resin was injected into the dry region and left to cure at room temperature. It is not known what effect this repair process will ultimately have on the local strength of this upper region. During the infusion, the fibres in this region had previously been wet out with resin before the majority of the resin had drained away. Therefore, many of these fibre tows were already coated with resin prior to the repair process. Ultimately, the success of this repair process depends on the extent to which the resin had penetrated all dry regions and the strength of the bond between the resin covered fibres and the fresh resin. This procedure was selected over other repair schemes due to budget and time limitations.

The outer surface of the demonstrator was of good quality and required no additional work because the tool surface was flat without any inlets/resin channels embedded within the surface. The inner surface required no further work and was already protected with a layer of peel ply. This would be removed just before assembly with the decks and bulkheads to ensure good bonding between components. Sharp edges where resin and/or fibres had extended over the edges of the part were grinded down to produce smoother faces that can be more safely handled by personnel.

5.13 Manufacturing process flow chart

Figure 123 outlines the manufacturing process that was used to produce the demonstrator section. This is a further iteration on the initial flow chart presented in Figure 86. The core process line represents the critical path that limits the overall duration of the process. Parallel tasks linked to core process steps must be completed before the overall process can continue. To maximise process efficiency, parallel tasks should be completed alongside the core process line at sufficient speed to avoid delaying the overall process. Red, green and purple represent the core process line, parallel tasks and initial setup respectively.

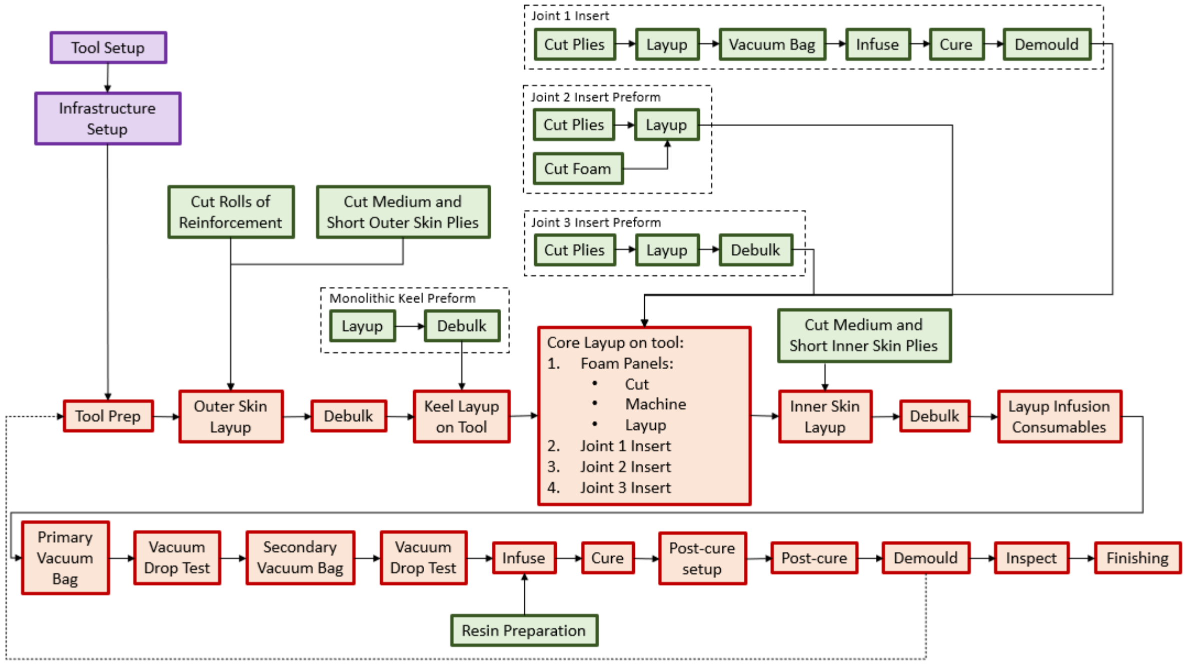


Figure 123: Demonstrator manufacturing process flow chart. Red = core tasks, Green = parallel tasks, Purple = Setup tasks.

5.14 Resources and time spent on manufacture

The time and resources required to complete the demonstrator manufacture are displayed in Table 42. In addition to these resources, a significant amount of work was done to develop the manufacturing processes, trialling alternative procedures and experimenting with materials. This work is not included in Table 42 as the data is intended to portray the manufacturing process only, as a baseline for a commercial procedure. This data is used at the end of this chapter to estimate resources required for an improved, scaled-up version of this manufacturing process for a full 75m hull shell.

An 8-hour working shift per day is assumed. The same colour scheme used in the manufacturing flow chart (Figure 123) is also used here, with red, green and purple representing the core process line, parallel tasks and initial setup respectively. The total resources for the demonstrator production are shown at the bottom of Table 42. These are presented for both sequential and parallel production options. Ideally, the green tasks would be conducted in parallel and therefore not contribute to the overall duration of the process. However, because this was a learning exercise for a one-off prototype, and available personnel were limited, many tasks were conducted sequentially instead. Both possibilities are presented to indicate the process duration for this demonstrator and for a more streamlined process. The entire demonstrator manufacturing procedure required 780 man-hours, greater than the 672-man-hour goal (Table 24). However, due to the novelty and scale of the study, this deviation is not thought to be a significant issue.

Table 42: Resources used to manufacture demonstrator.

	Task	Duration (hrs)	People	Man-hours
One-off setup	Tool setup/installation	16	4	64
	Resin mixing setup	16	1	16
	Creating preform tooling	8	2	16
	Gantry construction	80	1	80
	Scaffold tower construction	8	3	24
Hull shell manufacture	Tool preparation	16	2	32
	Layup outer skin	20	4	80
	Debulk outer skin	8	2	16
	Glass roll cutting	12	1	12
	Medium/short skin plies cutting and kitting	16	1.5	24
	Foam core cutting and machining	36	1.5	54
	Create monolithic keel preform	24	1	24
	Create joint 1 pre-cured support	28	1	28
	Joint 1 support cure	24	0	0
	Create joint 2 preform	4	2	8
	Create joint 3 preform	10	1	10
	Layup core; including all foam and preforms	20	1.5	30
	Layup inner skin	20	4	80
	Layup infusion consumables	8	3	24
	Apply primary vacuum bag	6	3	18
	Vacuum drop test	24	0.04	1
	Apply secondary vacuum bag	6	3	18
	Vacuum drop test	24	0.04	1
	Infuse	17	3	51
	Cure	48	0.02	1
	Post-cure setup	8	2	16
	Post-cure	48	0.02	1
	Demould	8	3	24
	Inspect	3	1	3
	Finishing	24	1	24

	Total Duration	**Hours**	**Days**	**Man-hours**
Total	**Setup**	**128**	**16**	**200**
	Hull Manufacture (all sequential tasks)	**462**	**57.8**	**580**
	Hull Manufacture (some parallel tasks)	**308**	**38.5**	**580**
	Entire Process (all sequential tasks)	**590**	**73.8**	**780**
	Entire Process (some parallel tasks)	**436**	**54.5**	**780**

5.15 Future Process Improvements

The production of the demonstrator prototype highlighted some key issues with both the part and the process. The next steps are to further refine the process and product design and implement these improvements on a full 75m long hull manufacturing process. This section discusses potential improvements to the process that could solve the quality issues specific to the demonstrator section.

5.15.1 Step Transition Refinement

The sharp transitions in sectional thickness at joints 1 and 2 are primarily responsible for the two large wrinkles in the upper skin laminate. The bulk factor in the dry material combined with the thickness of the outer skin means that preventing these wrinkles is extremely difficult. A combination of measures can be taken to reduce the size and severity of these wrinkles:

- Redesign the joint 1 and 2 supports with more gradual transitions in sectional thickness. This was successfully demonstrated at the keel/SP1 interface.
- Introduce periodic debulking of the inner skin during layup. This should reduce the bulk factor of the laminate as demonstrated during the debulking trials.
- Improve accessibility to laminators to provide greater, and more uniform compaction over each ply during layup, allowing for tighter layup tolerances around geometrical transitions. Saerflow should also be supplied with adhesive backing as the process of applying spray adhesive was not robust.
- If sharp transitions cannot be avoided in the design, they should be formed using pre-shaped high-density foam core sections to overcome the issues encountered with the joint 2 monolithic wedge.
- To better account for these unavoidable sharp transitions, "slip zones" may be incorporated locally around transitions within the inner skin layup. These consist of ply splice joints perpendicular to the fibre direction and allow greater slippage/movement of the plies during the vacuum compaction stage, which may help reduce the severity of wrinkles and bridging.

5.15.2 Infusion

Whilst the infusion was generally a success, the process highlighted the sensitive nature of large-scale vacuum bag resin infusions. One minor process issue at the very end of the process can lead to significant product defects. A more radical redesign of the product may be required to properly address the issues of general process robustness as manual application of vacuum bags may not be the most effective long-term strategy. The next chapter explores these more radical modifications in more detail. This section focuses on minor improvements to the existing process and product design.

It is not yet understood why the vacuum bags welded together at the end of the infusion. This was the primary cause of the dry region at the top of the part. Research is currently being conducted to understand why the bags welded together, and the results of this study will be used to implement process improvement in future manufacturing processes. Besides this, other modifications to the process that could prevent the dry region at the top of the part are as follows:

- Refine the resin mixture so that cure occurs sooner. Ideally, the resin cure front should follow the flow front closely, shortening the time that the resin spends as a liquid within the preform. This will reduce the severity of any effects caused by defects in the vacuum bag.
- Apply moderate heating (~50°C) to the upper region of the part immediately after the infusion is complete to accelerate resin cure.
- Ensure that at least one member of the workforce monitors the part until full cure is achieved. Remedial action can be implemented if issues are detected early.
- Use wider bore resin feed tubes to allow a faster resin flow. This will result in a faster infusion (~8 hours). The shorter infusion fits within a single work shift, which is more affordable and convenient.
- Improve the seals at all joints in the resin inlet feed tubes to reduce the likelihood of air leaks and hence voidage in the cured part (consider investigating alternative consumable infusion products).
- Conduct an optimisation study to determine the minimum level of mixing required to maintain suspension of toughening particles within resin in the “intermediate bulk container” (IBC). Excessive mixing can lead to additional air bubbles in the resin, resulting in an increased voidage level in the cured part. Potential de-gassing procedures may also be investigated as well.
- Whilst the fibre weight fraction of the demonstrator was acceptable, it is thought that additional improvements could be made to further increase fibre weight fraction if required/desired by the shipyard. The use of external pressure (up to 138kPa) on the vacuum bag has been demonstrated in literature to reduce laminate thickness and hence increase fibre volume fraction from 50% to 62% (M. Akif Yalcinkayaa, 2017). However, applying this external pressure over such a large area would require expensive pressurised tooling. The effect of this pressurisation on the likelihood and consequence of bag leaks would also need to be investigated. Alternatively, a patent exists that describes a process of applying external pressure to a moulding by submerging the vacuum bagged part in liquid (Paul J. Biermann, 2002). The logistics of lowering and raising the hull tool and preform into and out of a body of liquid to a sufficient depth, and the consequence of bag leaks could make this technique particularly challenging in practice.

Overall, the infusion process demonstrated here was shown to be robust and effective. The next steps are to reduce costs and scale up the process to create a production-ready procedure.

5.16 Cost and Scaling Up

For the composite hull shell to be commercially viable, further improvements to the process are required to reduce production time and cost. This section explores such improvements; applicable to both the demonstrator section and the full 75m long hull shell. The goal of this section is to bring together the knowledge developed thus far and present a viable manufacturing concept for the 75m long hull shell.

5.16.1 Differences between demonstrator and 75m hull shell

It is important to understand the differences between the demonstrator and the full 75m hull if the manufacturing process is to be effectively scaled up. The following points are identified as the key differences between the two:

- The hull is approximately 28 times the length of the demonstrator. The hull is also symmetric, meaning the full 75m hull is approximately 56 times larger than the demonstrator.
- The shape of the hull shell is assumed to be mostly consistent along the length of the ship with very slight changes in cross sectional shape.
- The hull contains additional details such as double curvatures and potentially sharp transitions around the bow and stern.

Excluding the bow and stern, the layup processes for the demonstrator (which are further refined below) are assumed to be applicable to the full length of the hull shell. The formation and layup of the joint supports together with the bagging procedure will need to be modified slightly to account for the increased length and surface area of the part.

For the purposes of this study, the 75m long hull is assumed to be a symmetric, extended version of the demonstrator section. The bow and stern are ignored at this early stage and implementation of these features are left for future work.

5.16.2 Further Accessibility Improvements

Improved infrastructure is required to provide suitable access to a full 75m long hull shell tool surface. Laminators should not walk on the preform during layup, bagging, or infusion to minimise the risk of foreign object inclusion within the preform and pin-hole leaks in the vacuum bag. This approach was shown to be effective during the demonstrator production. Whilst there are some examples of laminators walking directly on the preform and/or bagged surface in composite boatbuilding projects (Composites World, 2014) (Marathon Pacific Marines, 2011) (Galati Yachts, 2020), the author believes that this increases the risk of process failure (i.e. bag leaks that result in a laminate that does not meet the defect acceptance criteria for this project) based upon the research and experimental findings presented in this thesis. Furthermore, the higher materials cost associated with an infusion at this scale leads to a far greater financial consequence if the process fails compared to the smaller examples referenced. To provide improved accessibility without increasing the risk of process failure, movable platforms attached to overhead rails are suggested as a suitable alternative to the gantry platforms that were used for the demonstrator. This should provide flexible access to a much greater extent than was possible during the demonstrator manufacture. The scaffolding around the back of the tool surface should be extended around the entire hull shell, similar current composite boatbuilding setups such as (Galati Yachts, 2020).

5.16.3 Glass Reinforcement Layup

Modifications to the layup procedure are proposed to reduce workforce involvement and improve efficiency. The key change to this process is the direct deposition of material from the roll onto the tool, similar to commercial tape laying processes (Accudyne, 2019) (Danobat, 2018) (Electroimpact, 2019) (Mikrosam, 2020) (MTorres, 2019). This eliminates the costly and time-consuming ply handling tasks. The width of the glass reinforcement rolls is also increased from 1.25m to 2.5m, allowing for greater coverage of material in fewer layup steps. Figure 124 shows the modified process of laying material onto the tool.

To facilitate direct deposition of plies from roll to tool, the adhesive backing is applied on the opposite side of the reinforcement to what was used for the demonstrator. The roll of glass reinforcement is rolled across the tool, depositing plies of glass reinforcement whilst the backing film, now positioned on the outer surface of the roll, is simultaneously peeled away and stored on a second roller. A small roller is positioned behind the glass reinforcement roll to provide light compaction, positioning the ply onto the surface. A laminator will then use a hand roller to manually apply further compaction, firmly sticking the ply to the surface and matching any contours/details. The material deposition tool is mounted below a movable platform, providing access to the laminator as the plies are laid onto the tool.

It is important to note that this is not an automated process, but rather a manual, mechanised one. Current wind turbine blade manufacturing methods have also adopted a combination of mechanised/automated and manual layup techniques (Composites World, 2018). Whilst there are some differences in geometry between wind turbine blades and the hull shell case study, many of the layup challenges encountered in wind turbine blade manufacture are also applicable to this project. Wind turbine blade manufacturers have identified that the more complex curved regions of the blade geometries require manual layup techniques, whilst the relatively flat, longitudinal plies can be positioned using a semi-automated deposition tool.

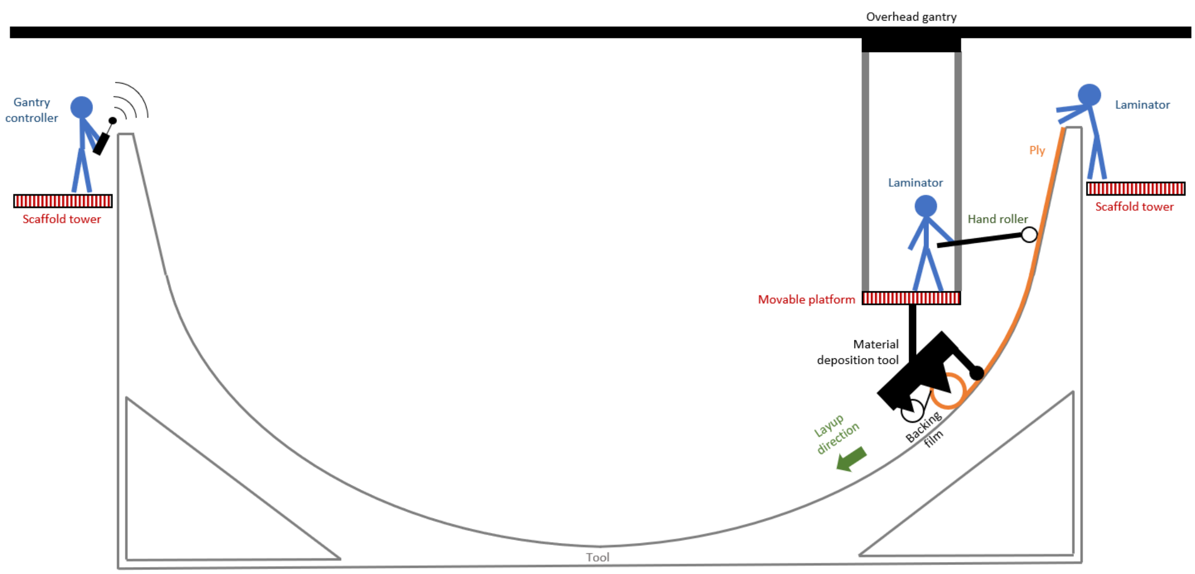


Figure 124: Revised glass reinforcement layup procedure for 75m long hull shell

The layup deposition tool is therefore manually controlled, and the pace is set by the laminator on the platform applying manual compaction. The deposition tool simply positions the plies in the correct location and orientation on the tool. The laminators perform the more complex and dextrous tasks of draping and compaction, and act as the final quality control check for each ply. The main driver behind this process is to maintain simple, cost effective technologies that are compatible with existing shipyards.

The roll of glass reinforcement rotates as the deposition tool moves down the part. There is no motor driving this rotation and tension pulls the ply off the roll, preventing wrinkles in the skin. The backing film roll is connected to the reinforcement roll via a 1:1 gear train, to provide smooth and steady removal of backing film as and when required.

Achieving the ply positioning tolerances using this proposed layup approach may be challenging. Further work is suggested to test existing overhead gantry cranes and potentially work with crane suppliers to understand if the ply positioning tolerance of ~+/-10mm is achievable. If conventional gantry cranes are not suitable, sensor solutions such as linear encoders and laser trackers are available that can provide positioning tolerances of 0.3mm-1mm. (SICK, 2020) (Hexagon, 2018).

Complexity within the layup process is reduced further by almost completely removing the need for ply patterns. For the demonstrator production glass reinforcement rolls were cut into predefined roll widths to create a staggered ply pattern. This is not necessary across most of the 75m long hull, as fixed-width plies can be staggered along the length of the hull. A 50mm offset between plies is suggested along the length of the hull. This is a manageable and achievable offset with the layup technology, whilst also resulting in no overlap of ply edges within the laminate skins. (45 plies per skin, 50mm offset per ply = 2250mm distance between the edges of the first and last ply, compared to the ply width of 2500mm). Furthermore, plies are cut to the desired length during the layup process, meaning this technology is valid for medium and short plies as well. The benefits of using this more direct layup approach are:

- Tighter controlled ply position tolerance compared to manual layup, resulting in smaller and more regular spacing between plies.
- Plies are staggered along the length of the hull with a 50mm offset between plies. This results in no overlap of ply edges in the laminate skins, and therefore eliminates grooves in the inner surface of the hull shell.
- Very little material preparation work (such as cutting of rolls/plies) is required prior to layup.
- Layup of glass reinforcement is rapid compared to demonstrator production.
- Compaction of plies onto the tool surface is more robust and consistent, reducing the risk of ply slippage, bridging and wrinkling.

5.16.4 Core Layup

Foam core panels could be laid up in bricks in the same process that was used during the demonstrator production. This procedure is easily scalable due to its modular nature. Unlike for the demonstrator, it is proposed that the foam panels be cut, machined, and sorted into kits prior to layup to streamline the process. Core kits are currently used in wind turbine blade manufacturing and are able to meet the tight 2mm gap tolerances for this application (Composites World, 2020). Based on the positioning tolerances of the demonstrator production, it is believed that these kits will be sufficient for this application.

The joint support details must be modified to accommodate the increased section length. It is proposed that each insert be made 2.5m in length and connected to adjacent inserts via scarf joints, as it is impractical to pre-make and layup 75m long inserts that precisely fit the shape of the hull shell. These scarf joints would need to be implemented in the next design iteration of the hull.

5.16.5 Infusion

The infusion process is almost entirely scalable to a full 75m long symmetric hull. It is suggested to keep the broad details of the infusion the same, including inlet and outlet positions. Two key changes to the process are suggested to scale up this scheme.

5.16.5.1 Redesign of monolithic keel inlet

The monolithic keel inlet for the demonstrator was designed to minimise risk of critical infusion issues, as there was only enough budget to make a single demonstrator. The surface across the thickness of the keel (where the inlet was placed) is not accessible on a symmetric hull section, and therefore not available for use as a resin inlet. This section must be a continuous monolithic laminate otherwise the strength and stiffness of the hull would be compromised. Resin inlets would therefore need to be positioned on the inner and outer surface of the keel instead.

It is proposed that two resin inlets be positioned at the mid-point of the monolithic keel on the inner and outer skin. Figure 125 shows the proposed infusion procedure for the symmetric monolithic keel. It is important to note that this is simply a concept, and further refinement through experimental trials and simulation is suggested prior to implementation.

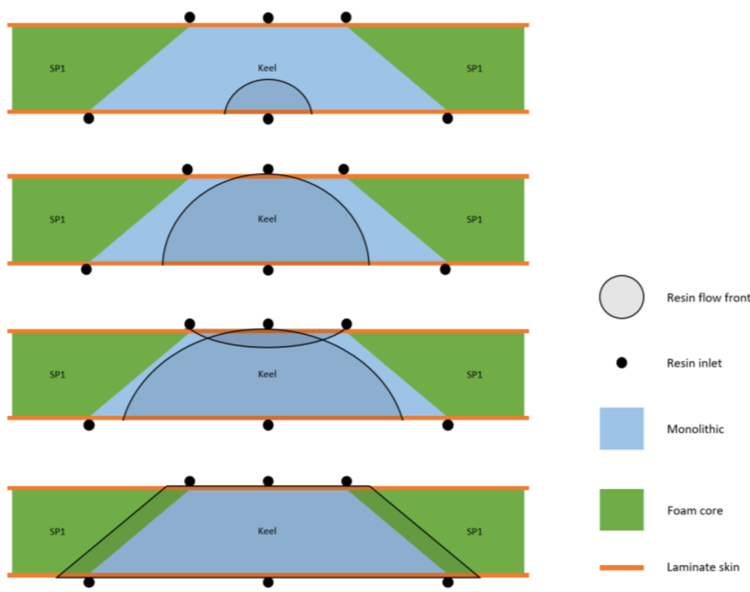


Figure 125: Concept for initial flow front progression through the thickness of the monolithic keel (symmetric hull shell)

The goal of this infusion step is to create a straight, regular flow front through the thickness of the section that will travel up the part to reduce the risk of infusion defects. Unlike with the demonstrator, it is not possible to start with a regular flow front, so one must be created. Resin is first introduced to the outer surface. When the resin has penetrated through the thickness and is visible on the inner surface, the top inlet is then opened. The number of Saerflow plies in the stacking sequence can be modified to alter the in-plane permeability of the monolithic keel and stop the resin racing across the outer skin towards SP1. The taper between the keel and SP1 has also been reversed to better achieve the desired resin flow. Through-thickness flow channels may be required if this is insufficient; however, a trade-off study would need to be conducted to understand the effect on the structural properties of the keel. The fundamental driver behind this concept is to minimise the risk of dry areas forming by increasing flow front visibility when resin inlets are opened. As with the demonstrator, it is preferable to maintain a single resin flow front as this significantly reduces the risk of dry regions.

5.16.5.2 Redesign of inner and outer skin resin inlets

Access into the thickness of the shell structure is not possible for the full 75m hull as it was for the demonstrator, so it is difficult to implement the through-thickness connection between the inner and outer resin inlets. Furthermore, implementing through-thickness resin tubes into the structure could compromise the structural performance of the hull shell. It is therefore proposed that separate resin inlets are implemented for the inner and outer skins, with the latter being integrated into the tool surface. As previously discussed, this will lead to greater tooling setup and maintenance costs, as well as an additional finishing step on the outer surface of the cured part. However, this is thought to be the most robust option available without compromising structural performance.

More fundamental modifications to the infusion process could be explored in further work to address the high-risk nature of this procedure. For example, dividing the infusion into smaller, sequential stages may act to reduce the risk of process failure and result in a more manageable infusion process. In this scenario the hull shell would still be infused in a single shot to preserve the advantage of producing a continuous structure with no joints or obvious structural weaknesses. Dividing the infusion in this way could allow easier monitoring of the process and more cost-effective implementation of injection machines (lower overall resin injection rate required, so less machines required). The precise details of how this process would be implemented would require extensive research.

5.17 Improved Process – Predicted Resources

In this section the resources required to manufacture the 75m long hull shell are estimated. It is assumed that all improvements previously discussed have been implemented, and estimations are based upon the data recorded during the demonstrator production. As with the demonstrator production, each task is colour coded depending on whether it is a core process task (red), parallel task (green) or setup task (purple). Totals are also presented at the bottom of Table 43 assuming all green tasks are conducted in parallel to the core process. The data indicates that a repeatable hull shell manufacturing process would take approximately 57 working days to complete. For comparison, it took approximately 58 days to produce the demonstrator section, indicating the significant effect of the improvements to the process.

Table 43: Predicted resources for revised 75m hull shell manufacturing process.

	Task	Duration (hrs)	No. People	Man-hours
One-off setup	Tool setup/installation (excl. tool creation)	80	20	1600
	Resin mixing setup	8	2	16
	Creating preform tooling	8	10	80
	Tool surface access infrastructure setup	80	20	1600
	Scaffold tower construction	80	20	1600
Hull shell production	Tool preparation	6	10	60
	Layup outer skin	22.5	20	450
	Layup monolithic keel	20.2	10	202
	Apply vacuum bag	36	20	720
	Debulk outer skin	24	0.08	2
	Remove vacuum bag	2	20	40
	Create joint 1 pre-cured support	60.6	10	606
	Joint 1 support cure	24	0.04	1
	Create joint 2 preform	12	10	120
	Create joint 3 preform	12	10	120
	Foam core cutting and machining	24	10	240
	Layup core; including all foam and preforms	50	20	1000
	Layup inner skin	22.5	20	450
	Layup infusion consumables	16	20	320
	Apply primary vacuum bag	36	20	720
	Vacuum drop test	24	0.08	2
	Apply secondary vacuum bag	36	20	720
	Vacuum drop test	24	0.08	2
	Infuse	8	10	80
	Cure	48	0.08	4
	Post-cure setup	8	10	80
	Post-cure	48	0.04	2
	Demould	8	20	160
	Inspect	4	4	16
	Finishing	16	20	320

	Total Duration	Hours	Days	Man-hours	ROM Cost (£)
Total	Setup*	256	32.0	4896	220,000
	Hull Manufacture	459	57.4	5350	1,025,000
	Entire Process	715	89.4	10246	1,245,000

**Does not include the labour and materials costs required to create the tool, as this was beyond the scope of the work conducted by the author*

It should also be noted that 4 people were working on the demonstrator production, whilst the scaled-up process assumes 20 people are available. The procedure would work with as little as 4 people, although it would take approximately 5 times longer. An initial estimate of 20 people was made based on the personnel required for the demonstrator production and the size difference between the demonstrator and a 75m hull. 5 teams of 4 are assumed to work simultaneously at different positions along the 75m hull, thereby reducing total production duration. Each team will require a local gantry crane to lift materials into place and layup the reinforcement. 5 teams working simultaneously therefore requires 5 gantry cranes to be installed on a single set of rails that span the entire hull length. A total of 5 gantry cranes was identified as a realistic maximum, but ultimately the number of teams will be limited by the number of gantry cranes available in the shipyard. It is important to note that the shipyard will select the most appropriate number of people based upon additional factors such as available personnel and infrastructure, required production rate and the workload across the shipyard.

A rough order of magnitude (ROM) production cost estimate is presented at the bottom of Table 43. This estimate was made by considering labour, overhead and raw materials costs. Based on the materials used in the demonstrator production, it is assumed that approximately £784,000 worth of constituent composite (and consumable) materials will be required to manufacture the 75m hull shell. A breakdown of these material costs is provided in Appendix A.7. Labour rates and overhead costs are based on Airborne UK estimates. A breakdown of these costs is not presented directly in this report for confidentiality reasons.

5.18 Improved Process – Manufacturing Process Flow Chart

The manufacturing process flow chart for the 75m hull shell is shown in Figure 126. Red, green and purple represent the core process line, parallel tasks and initial setup respectively. This flow chart is similar to the demonstrator manufacturing process (Figure 123), with three key differences to streamline the process:

- Skin laminate reinforcement preparation tasks (roll/ply cutting) have been removed, reducing the total number of process steps.
- The foam panel preparation steps (cutting and machining) are taken out of the core process line and instead are performed as parallel tasks.
- The monolithic keel is now laid up directly onto the tool as part of the core process line. This eliminates unnecessary preform transportation and debulking steps.

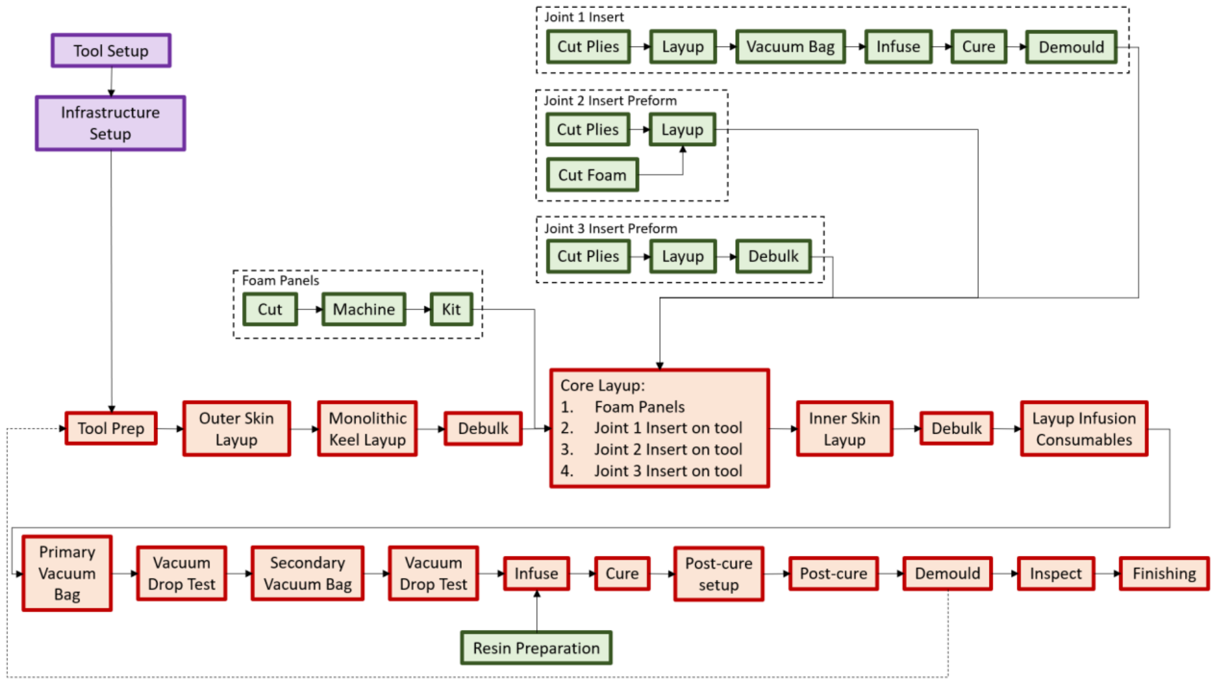


Figure 126: Manufacturing process flow chart for 75m long hull shell

5.19 Improved Process – Value Stream Map

A value stream map is a useful tool for highlighting the inefficiencies of a process by separating tasks into those that add value to the product, and those that do not. Value-added tasks are defined in this report as tasks which directly or indirectly add value to the product. Non-value-added tasks can increase production costs and duration unnecessarily, so these tasks should be minimised to reduce unnecessary costs, thereby increasing company profits and/or reducing product sale price. Definition of what classifies as a non-value-added task may vary depending on the company and application. In this case study the author considers tasks such as transporting material throughout the factory, employees waiting at workstations due to unoptimized workflow, and cleaning tasks due to excessively untidy or unorganised work areas to be non-value-added tasks. Efficient factory/shipyard layouts and process scheduling can reduce the level of non-value-added tasks.

A value stream map has been created by the author and is presented in Figure 127 to identify the proportion of non-value-added tasks within the proposed manufacturing concept and to demonstrate its potential usefulness as a management-level tool that could be used to evaluate future iterations of this manufacturing process.

Figure 127 indicates that approximately 90% of the time spent manufacturing the composite hull shell is value-added. The value stream map highlights a high proportion of the non-value-added production time lies within the tool preparation and material layup procedures. Employees must wait between application of individual coats of release agent, whilst the layup tool must be continually reloaded with new rolls.

This tool allows the engineer to identify key problem areas within the process and focus improvements towards these areas to potentially reduce the total non-value-added processing time. For example, an automated/robotic tool preparation device could clean the tool and apply tool release agent whilst the workforce simultaneously prepares the joint support features. This modification could simultaneously reduce non-value-added time and reduce the total number of employees required for the hull shell production. It is important to note that some non-value-added time is inevitable, especially for such a manually focused manufacturing process. Tasks such a workshop clean-up should not be avoided but may be made more efficient by applying LEAN manufacturing solutions.

5.20 Conclusions and future work

This chapter presents a complete account of the demonstrator manufacturing procedure, which builds upon the design refinements and process developments presented in the previous chapters. The demonstrator manufacture represents the conclusion to the rapid development approach that was proposed and employed in Chapters 3 & 4. The results of this manufacturing study indicate that the rapid development approach was a success. The combination of focused experimental tests and expert manufacturing knowledge and experience enabled the author to address the key manufacturing challenges prior to the demonstrator production, and a suitable manufacturing process and good quality demonstrator section was produced in approximately 18 months.

Despite rapid process development approach, a significant amount of learning was gained from the demonstrator manufacture, including appropriate layup tolerances and difficulties creating certain preform features (such as the joint 2 shear webs and monolithic ledge). The novelty of this manufacturing project meant that this knowledge cannot practically be gained from small scale trials or simulations, so physically trailing the process at full-scale was extremely useful and insightful. The author believes that a good balance was struck between the extent of process development experiments and activities in Chapter 4 and the overall goal of producing a workable demonstrator section. If this rapid development approach had not been used to focus the work toward the key manufacturing challenges, it is possible that the process development could have expanded significantly in terms of both cost and duration.

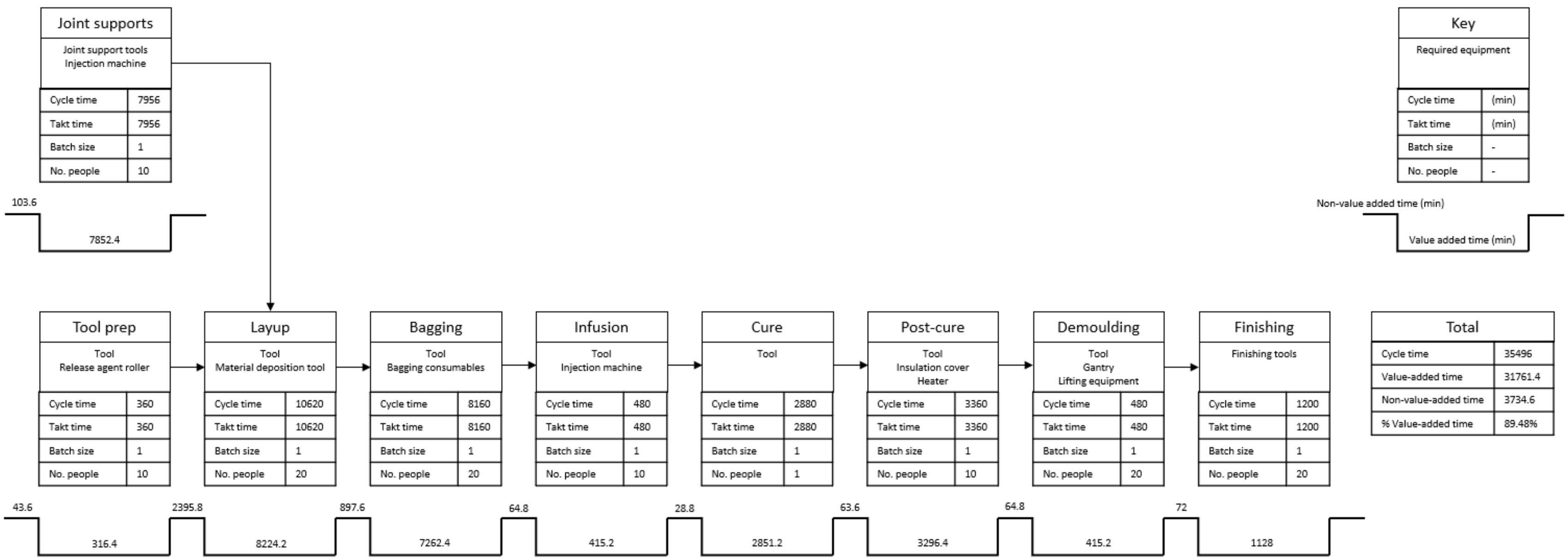


Figure 127: Value stream map for proposed 75m hull shell manufacturing procedure

The demonstrator section was produced to a good level of quality, with the majority of the part requirements and defect acceptance criteria being met. The key quality issues of the part were the large dry region at the top of the section and the two large wrinkles within the inner skin at the structural transitions. The dry region was repaired via a second infusion stage. Improvements to the layup process and hull shell design have been suggested to reduce the severity of the wrinkles.

The knowledge gained through this manufacturing study has been applied to generate a scaled-up manufacturing procedure for a symmetric 75m hull shell. Production resources and costs estimates are provided alongside a revised process flow chart and evaluation of value-added-tasks using a value stream map. Further work is suggested to prove the applicability of the process improvements and modifications suggested. The resource and management-level analysis presented at the end of this chapter may also be useful for quantifying and evaluating the suitability of these future improvements. The work presented in this chapter addresses the three key challenges identified in Chapter 3:

- **Scale, Geometry, and Accessibility:** A combination of suitable material selection and process development allowed a stable preform to be created on the demonstrator tool. An access gantry and scaffold tower were setup to provide moderate access to the tool surface. Some areas were still difficult to reach, leading to minor issues during the layup procedure. These have been identified and future improvements have been suggested.
- **Vertical infusion:** The part was successfully infused up to 6m during the initial infusion process. A minor resin drainage issue resulted in a dry patch forming at the top of the part, although modifications have been suggested to avoid this occurring in the future.
- **Variable shipyard environment:** Record of temperature and humidity variation shows the manufacturing process is generally insensitive to atmospheric variations within a typical factory. Further work should be conducted to explore sensitivity of the process to the full temperature and humidity variation range specified by the shipyard.

This concludes the feasibility study into the manufacture of a fully-composite, infused hull shell demonstrator section. Following the work presented in the last three chapters, the hull shell demonstrator was shipped to project partners in the Netherlands where it was assembled together with composite decks and bulkheads. The complete assembled structure would later be structurally tested. The reader is encouraged to refer to the RAMSSES project website for further information on these activities: https://www.ramsses-project.eu/

There are two paths of research that branch from the manufacturing study presented in this thesis. The manufacturing process concept proposed in this section could be refined further and implemented in a shipyard to produce a prototype 75m hull shell. This future work includes infusion process refinement and simulations, development and testing of a new material deposition tool, modifications to the hull shell design and additional manufacturing details around the bow and stern. These changes preserve the advantage of producing a continuous hull shell with no joints or obvious structural weaknesses.

Alternatively, more radical changes to the process can be considered. The highest process risk identified in this project was the integrity of the vacuum bag over such a large area. The demonstrator manufacture showed how a slight issue at the end of an otherwise successful process can cause large defects, leading to costly repair work or potentially scrapping the part. To properly address this risk requires significant changes to the fundamental aspects of the manufacturing process and part design. As this chapter is intended to be a feasibility study, such changes are not appropriate to discuss here. The following chapter explores this alternative route in more detail, investigating further improvements to process efficiency and cost by introducing significant levels of process automation.

6 AUTOMATED MANUFACTURING SOLUTIONS FOR LARGE INFUSED COMPOSITE STRUCTURES

A manual manufacturing process was presented for a fully composite ship hull shell in chapter 5. During this study, several manufacturing challenges related to layup, infusion and demoulding were highlighted. A revised manufacturing solution was presented to address these issues; however, this solution is most suited to a one-off/small-batch production style. For continuous production of commercial composite vessels, more fundamental modifications to the structural design and manufacturing process are required to enhance competitiveness against conventional steel manufacturing processes.

In recent years there has been an increased global interest towards the adoption of automated manufacturing techniques within composite production lines. One of the greatest limitations of most fibre reinforced composite products is the high manufacturing costs, which are generally associated with the greater complexity of the manufacturing process compared to other materials such as metals.

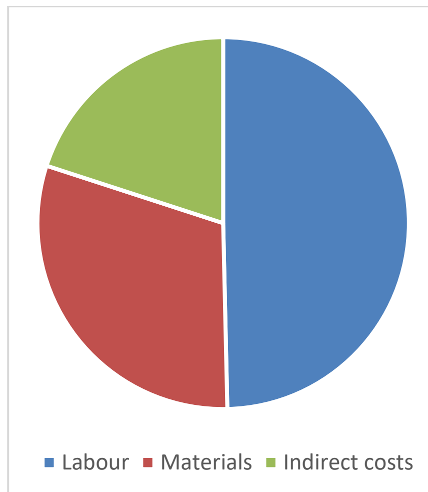


Figure 128: Simplified cost breakdown for hull shell demonstrator manufacture.

Conventional composites manufacturing processes generally feature significant labour costs due to the nature in which they have evolved over time. Material suppliers have typically produced products (prepreg, dry reinforcements, hand-mixed resins) that are designed to be handled by a human operator. Manual layup of materials over a tool has generally been the preferred way to manufacture composite structures with complex geometries and high mechanical performance, and vacuum bags are commonly used in larger infusion processes to reduce the costs associated with large tooling. Creating the preform and applying the vacuum bag and associated consumable materials are dextrous tasks that require a skilled workforce. Companies therefore rely on the expertise of their employees to create high quality composite products, with each employee being a critical part of the production process. This results in a labour-intensive manufacturing process. Figure 128 shows a simplified cost breakdown for the hull shell demonstrator manufacture featured in chapter 5 and indicates that labour costs contributed to approximately 50% of the total demonstrator production costs. This can be linked to the challenging tasks of laying up, vacuum bagging, infusing and demoulding a part of this scale. The labour costs must therefore be reduced if the composite hull shell is to a be a commercially competitive product. To do this, the dependency on trade skills must be reduced.

High labour costs are leading more companies to consider automation to enhance their competitiveness within the global market. Automated manufacturing processes are commonplace in the food, pharmaceutical and automotive industries, and are most effective when applied to simple, repetitive tasks that are difficult or costly to conduct manually. The scale and repetitive nature of the composite hull shell manufacturing process lends itself to this technology, as limited tool access combined with repetitive and physically demanding manual tasks can increase the likelihood of defects and delays. In this application, automation can lead to higher production rates, improved quality control, 24/7 production, lower production costs, reduced human exposure to harmful chemicals, greater lifting capacity and a larger working envelope/reach. To effectively implement this technology, the composite product may need to be redesigned to accommodate automated manufacture.

This chapter explores the benefits of incorporating automated technologies into the manufacture of the two case studies selected in Chapter 1: a composite tidal turbine blade and a composite hull shell. Due to the focus of the previous manufacturing study on the hull shell case study, this investigation will focus on the design and production of a 75m long hull shell with a constant cross section (neglecting bow, stern and other details). However, a short section is also included for the tidal turbine blade, drawing on the similarities between the two structures where appropriate. This work begins by defining a list of requirements for the automated hull shell manufacturing process. Automated manufacturing concepts are then presented and evaluated against relevant criteria. The most suitable automated manufacturing concepts are selected for each stage of the manufacturing process and are then combined to create a concept for a fully automated production line. Due to the complexity of fully implementing automated solutions within a commercial manufacturing process and the limited scope of this project, this work will only feature a top-level technical analysis to develop a suitable manufacturing concept. Further refinement and physical implementation are left for future work.

6.1 Requirements of the automated process

This section outlines the key requirements of an automated composite hull shell manufacturing process. These requirements will help guide the generation of a suitable automated manufacturing concept. The author decided to focus on the hull shell case study due to the experience gained in the previous manufacturing study presented in Chapters 3 to 5.

The manufacturing process presented in chapter 5 highlighted the limitations of a manual composites manufacturing process of this scale and complexity. Seven key challenges have been identified that must be overcome if the manufacture of a full composite hull is to be commercially viable. From these challenges seven process requirements are devised to guide the development of the automated manufacturing concept. These requirements are **highlighted in bold.** The automated manufacturing process that is proposed at the end of this chapter shall be evaluated against these requirements.

6.1.1 Shipyard logistics

Transportation of large quantities of materials is required to produce such a large composite structure. 2.5m wide rolls of reinforcement with a mass of 300kg each must be handled safely and loaded into cutting/layup equipment. Large blocks of foam core 2x1m in area must be laid onto the tooling in the correct location and orientation. Many tonnes of resin must be safely transported, stored and mixed on site. Conducting these tasks with only technicians is both challenging, costly and potentially unsafe. Shipyards contain the necessary infrastructure to transport large objects such as partial ship assemblies and tools, however these solutions are not fully automated and lack compatibility with some constituent composite materials such as the resin. Composites manufacturing facilities such as clean rooms, ovens, vacuum bagging stations and strict temperature-controlled environments are not typically present within steel shipyards. These can be added at the expense of high capital investment and disruption to production as the shipyard layout is redefined. Furthermore, shipyard workers will need to be retrained to work with composite materials. The level of retraining will depend on the amount of changes made to the manufacturing process. **The proposed manufacturing concept must be compatible with existing steel shipyard practices and contain the necessary equipment and infrastructure to handle and store large quantities of constituent composite materials.**

6.1.2 Layup

During the manufacture of the demonstrator, a large quantity of glass reinforcement was laid onto the tool. As this was only a section of the hull, it was possible to easily gain access to the sides and bottom of the part during layup and infusion. This would not be possible for a full hull shell, and the tools and equipment used in chapter 5 (e.g. access gantry, layup tool) would not be applicable. **An alternative solution is required to allow full access to the entire tool surface without using the tool surface as a means of moving around, as this could compromise the quality of the part.**

6.1.3 Tooling

Creation of a 75m hull tool is both expensive and time consuming. The cost and time related to the cleaning and preparation of the tool for each cycle must also be considered. With such a large tool area to work with, it is possible for a technician to miss certain areas, which can lead to issues during the demoulding step. **An alternative solution is required to reduce the costs associated with tooling and improve the reliability of tool preparation procedures.**

6.1.4 Infusion

The infusion process proposed for the demonstrator is somewhat risky due to the variability in the process and potential for leaks. When scaled up to a 75m hull, the risks associated with a one-shot infusion become too great. The monetary value of the materials on the tool would exceed 800k Euro, and the risk of scrapping it all due to a process fault is simply unfeasible. Depending on the issue, rework/repair may possible but expensive. **An alternative solution is required to reduce the risks associated with infusing such a large structure.**

6.1.5 Hazardous environment

The manufacture of a large composite structure combines the risks and hazards to the workforce of both general composites manufacture and large-scale construction. The workforce will be required to wear substantial PPE to address the risks whilst working in such a hazardous environment. Furthermore, the factory must be setup in such a way to minimise material contamination and exposure to hazardous chemicals. This would require a significant change to current steel shipyard practices. **An alternative solution is required to reduce the risks imposed on the workforce and minimise changes to the current steel shipyard layout.**

6.1.6 Cost

Material and labour costs represent the majority of the manufacturing costs for the hull shell demonstrator. These costs are typically lower for conventional steel assemblies due to simpler, more streamlined processes and more affordable standardised steel materials. The primary advantage of composites in this application is the enhanced long-term durability and reduced vessel maintenance costs, although end-of-life recycling/disposal is more difficult. A full life-cycle assessment is required to fully understand the cost benefits of a composite hull (future work). Even so, reductions in manufacturing costs are beneficial and should be explored. **Automated solutions are required to reduce manufacturing costs to enable a composite hull to compete with the steel alternative.**

6.1.7 Quality

When manufacturing such a large structure using manual methods, it can be difficult to control the quality of the part due to potential variations in the manufacturing process. The variability in the manufacturing process is much greater than for steel structures, and so a greater level of process control and traceability is required. Automation equipment can help improve the level of control over each process step. Integrating these steps together to achieve complete automated control and traceability across the manufacturing process will streamline the quality control process, reducing the risk of defective parts. **An automated closed control system is required to improve process robustness and quality control.**

6.2 Concept for an automated composite hull manufacturing concept

A concept for an automated composite hull production line has been developed using existing technologies available on the market. The goal of this work is to highlight the broad advantages of automation for this application, avoiding in-depth technical analysis of individual solutions. This work outlines the first steps towards developing an automated composites manufacturing process.

The manual manufacturing process that was previously developed (Figure 123 in chapter 5) is used as a baseline for this study. Every manufacturing step is considered, with several automation concepts being generated for each. The process steps are: Tool preparation, material preparation, reinforcement layup, foam core layup, vacuum bagging, infusion, cure and post-cure, demoulding, and finishing.

A number of automation concepts are proposed for each of the key process steps that make up the hull shell manufacture. Where appropriate, these are evaluated against a range of relevant evaluation criteria. The most suitable solutions for each process step are down selected and then brought together to form a complete concept for an automated manufacturing process, which is evaluated against the requirements outlined at the beginning of this chapter. Finally, the automated manufacturing concept is compared with the manual approach to demonstrate the potential benefits.

6.2.1 Generation of concepts

This section outlines the automated manufacturing concepts generated by the author for the hull shell manufacturing case study. A top-level comparison between different concepts is presented for each stage in the process. The evaluation methodology that was presented in Section 3.3 and used throughout the manufacturing process development in Chapters 3 and 4 is used here to identify the most suitable options. Unless otherwise stated, evaluation criteria are all given an equal weighting of 1. The reader is encouraged to refer back to Section 3.3 for details of the scoring system used in these evaluation matrices.

6.2.1.1 Tool preparation

Tool preparation describes the process of cleaning the tool after demoulding a part and then re-applying release agent. This can be a laborious task for larger tooling and represents a significant portion of the overall labour cost. Cleaning the tool and applying release agent are not complex tasks, and as a result the technician's skillset is not being fully exploited. The workforce could therefore be doing other, more complex tasks where they bring greater value and automation could be used here to reduce operational costs.

As the tool preparation process is already quite simple, it is proposed that an automated solution be developed to replicate this manual process. A tool preparation end effector is proposed which features a nozzle to spray release agent onto the tool and a roller that passes over the sprayed area to provide an even coating. This end effector could be attached to an overhead gantry or robot arm (depending on the required working envelope) and follow a pre-determined path across the tool surface. The programmed path, combined with internal sensors on the spray nozzle will enable a quality control system to be applied that monitors the application of release agent, thereby ensuring a complete and even coverage across the entire tool surface. This is a significant improvement on the manual process, where human error can result in untreated areas on larger tools.

6.2.1.2 General material preparation

There are several logistical steps that must be completed prior to layup of constituent materials onto the tool. When the materials are received by the factory or shipyard, they must be stored in a safe and ordered fashion. The material supplier will detail a suitable range of storage temperatures as not to diminish the shelf life of the product. As detailed in chapter 2, the sizing on dry reinforcements can degrade over time due to high storage temperatures and humidity. Resins can also slowly cure due to excessive temperatures, and peroxides and accelerators may pose a fire risk if stored at high temperatures.

Upon delivery of materials, details such as the type of material and amount must be recorded on a centralised database, after which the material is assigned a batch number for traceability and process control. Barcode stickers on the material packaging are an affordable and efficient method for assigning batch numbers, and a barcode scanner can be integrated into automated equipment to monitor the flow of materials throughout the factory. Traceability of materials throughout the production line is crucial as it helps to identify the sources of processing issues.

When the materials are ready for production, they must be transferred from the storage facility to various positions on the factory floor. There is a variety of automation equipment that can be used to achieve this. Three concepts are investigated below and evaluated against the following criteria:

- **Loading capacity:** Maximum size and weight of objects that can be safely transported.
- **Logistical capacity:** Maximum number of separate movement tasks that can be performed at once.
- **Flexibility:** Ability to react to process changes and modifications to factory floor layout.
- **Robustness:** Likelihood of issues and faults within a shipyard environment.
- **CAPEX:** Initial setup cost.

Concept 1: Gantry system

These systems are generally used to move large, heavy items across large areas and as a result are commonplace within shipyards. They are generally robust systems that operate within a fixed working envelope. A gantry with a high load capacity can be used to transport almost any object used for a composite manufacturing process within a shipyard. A single gantry can therefore take the place of multiple transportation systems. As steel shipyards typically use gantries as part of their existing infrastructure, it seems logical to integrate this solution within the proposed manufacturing concept.

Concept 2: Cable bot

The cable bot's lightweight tension-cable design is most suited for moving small/medium sized objects such as pallets or rolls of reinforcement (Technalia, 2013). Its structurally efficient design and modular construction allows for reduced CAPEX and improved flexibility over a gantry for more localised tasks. This technology is not well suited for the transportation of larger, heavier assemblies, as scaling up this concept would negate the structural efficiency of its design. A cable bot would be very effective at performing a smaller, localised task to reduce the number of tasks performed by the existing gantry system.

Concept 3: Automated vehicles

This concept is more commonplace in the automotive industry and features a number of self-driving electric vehicles that move various objects around the factory (National Robotics Engineering Centre, 2020) (Fetch Robotics, 2020). These vehicles have an inbuilt vision system that enables them to navigate the factory. A centralised system could be used to integrate separate pick and place stations to facilitate loading and unloading operations. This concept is highly flexible as individual vehicle paths can be reprogrammed as required. However, they also take up space on the factory floor which may cause logistical issues.

Evaluation of concepts

The three material transportation concepts are evaluated in Table 44 against the defined criteria.

Table 44: Evaluation matrix for material transportation concepts.

	Concept 1	Concept 2	Concept 3
	Gantry	**Cable bot**	**Automated vehicles**
Loading capacity	Gantry systems are designed to withstand high loading and can be used to move large, heavy objects such as tooling and resin IBCs.	Cable bots are generally used to move small and medium sized objects such as pallets and rolls of reinforcement.	Automated vehicles are generally used to move small and medium sized objects such as pallets and rolls of reinforcement.
Logistical capacity	This system can only perform a single task at a time. Multiple gantry systems can be mounted onto a single set of rails; however, this can restrict the movement of individual systems as they cannot move past each other on the rails.	This system can only perform a single task at a time. As with concept 1, multiple cable bots could be integrated to work within the same space at the expense of restricted movement.	Multiple vehicles can be deployed to perform a number of simultaneous tasks.
Flexibility	The gantry system is a large, fixed infrastructure that is difficult and costly to modify to accommodate layout modifications compared to concepts 2 and 3.	Cable bots are modular in construction and can be disassembled and redeployed to accommodate process and layout changes.	Movement paths can be modified easily. There is no fixed infrastructure, so this concept is very flexible.
Robustness	Gantry systems are designed to be robust and operate within harsh industry conditions. Objects are transported in the air above the factory floor, minimising disruption to production.	Cable bots rely on cable tension and failure in a single cable could cause a complete failure of the system. The cable bot would need to be designed to withstand knocks within a shipyard environment. Objects are transported in the air above the factory floor, minimising disruption to production.	Vehicles move around on the factory floor so there is a greater chance of collision and general disruption to the production line. An automated vehicle may encounter issues navigating a busy shipyard.
CAPEX	Gantry systems can be expensive due to their size and robust construction.	Cable bots can be more cost efficient than gantries due to their simple construction.	Systems can be costly due to sophisticated technologies.
Total score	10	10	10

It is evident from Table 44 that no concept stands out as the best universal choice. Instead, one should consider where each concept would be most applicable within a shipyard. Gantries already exist within shipyards and are ideal for moving large, heavy objects. A cable bot would be best suited to moving composite materials from storage to the tool if these two areas are located close to one another. Automated vehicles could be suitable as an additional flexible system to transport individual rolls of reinforcement throughout the factory; however, they are not considered any further in this proposal due to robustness concerns within a shipyard environment. It is therefore proposed that a global gantry system is used to provide general transportation of tooling, components and large quantities of materials, with a smaller cable bot being installed to perform localised tasks such as moving raw composite materials from storage onto the tool.

6.2.1.3 Foam core preparation

The foam core is delivered to the factory in flat sheets of 1x2m area. These must be prepared for layup so that the sheets conform to the curvature of the tool. This can be done in one of two ways:

Concept 1: Thermoforming

Foam core sheets are heated to high temperatures and formed under vacuum into curved panels of pre-determined shape (Curveworks, 2018). The resulting core sheets match the tool curvature, eliminating the need for draping and greatly simplifying the layup procedure. The varying geometry of the hull shell will require panels of different curvatures. This could be achieved either with multiple thermoforming tools or a single variable geometry tool. The latter can provide an additional level of flexibility to accommodate design modifications and alternate ship designs.

Concept 2: Draping

A more conventional method for ensuring a foam sheet conforms to a curved surface is to machine slits through the thickness to provide a certain level of drapeability, as outlined in chapter 3. Creation of these features requires an additional machining step, and their presence in the foam core results in a greater level of resin uptake during the infusion process, increasing material cost and structural weight. This process can create foam sheets that generally conform to most curvatures, although the level of conformity is dependent on the frequency of slits. Gradual double-curvatures may be possible with this approach, however numerous slits would be required in multiple directions due to the high sheet thickness. These foam sheets can be difficult to handle due to their enhanced flexibility, which may pose problems when integrating automated handling solutions.

Evaluation of concepts

In this case an evaluation matrix is not required to select the most appropriate solution. Thermoforming clearly appears to be the most suitable option for this application. Both options feature an additional foam processing step, which can be performed in-house or by a third party. However, thermoforming produces foam sheets with a greater level of conformity that are easier to handle. The reduced resin uptake of thermoformed panels also provides a cost and weight benefit.

6.2.1.4 Reinforcement layup

The reinforcement must be transferred from materials storage onto the tool in the correct position and orientation. Three layup concepts are considered and evaluated against the following criteria:

- **Range of geometries, ply shapes and local details.** The majority of the hull layup is constructed of simple ply shapes across single-curvature surfaces using quasi-isotropic material. This is ideal for laying up wide rolls of off-the-shelf material. Ply lengths vary throughout the preform, so the proposed concept must be able to effectively cut plies to the correct length.
- **Maximum ply size.** The largest sized ply that can be handled by the technology. Smaller plies may negatively impact structural performance, whilst larger plies can lead to reduced layup times.
- **Process flexibility and upscaling.** Future modifications or improvements to the product design are a possibility. A greater level of flexibility within the process will accommodate product variations at a lower cost and reduced equipment downtime. The current trend is to manufacture progressively larger ships out of composite materials. It is reasonable to believe this trend will continue, so the chosen manufacturing process should be up scalable to accommodate larger ships hulls in the future.
- **Risk of process failure.** This combines both the likelihood and consequence of process failure due to concerns related to process robustness and other technical challenges.
- **Ease of installation.** Whilst not a critical factor, this must be considered to some degree as installation costs will contribute to overall setup costs. One major barrier to entry for automation technology is the time, cost and complexity related to setting up systems in the end-user's factory or shipyard. This includes additional infrastructure, training and changes to working practices that must be implemented to effectively utilise the automation equipment. The shipyard may also wish to modify or move the process line. A "plug and play" design approach could be considered for greater flexibility.
- **Deposition rate.** Faster deposition rates allow products to be manufactured quicker. This factor primarily concerns the rate at which material can be delivered onto the tool. To allow a fair comparison between each concept, this will include the time taken from loading raw material into the device to the deposition of material onto tool.
- **CAPEX.** At this stage it is difficult to compare accurate values for CAPEX between concepts. Estimations are based upon existing solutions and estimated development work required.
- **OPEX.** It is predicted that the operational costs for these automated concepts will be lower than equivalent manual processes. However, there may be variations in OPEX between the automated concepts due to the number of processes/equipment required.
- **Effect on structural performance.** Some modifications to the process may require redesign of the product. This could impact structural performance.

Concept 1: Basic ATL

Figure 129 presents a rolling end effector that is mounted to a gantry system to provide additional degrees of freedom for positioning plies on a curved tool surface (Accudyne, 2019) (Danobat, 2018) (Electroimpact, 2019) (Mikrosam, 2020) (MTorres, 2019). Ply cutting functionality is built into the machine. Laser tracking equipment can be used to correct for system inaccuracies in real time, allowing for less accurate and more affordable gantry systems to be used to meet layup tolerances (Hexagon, 2018). This system is suited to simpler geometries such as the simplified hull shell but may struggle with more intricate local details such as the bow or stern. To be fully versatile for this application, this system may require interchangeable ATL end effectors with different tape widths and cutting functionalities.

The major advantage of this system is its ability to layup material directly onto the tool, thereby reducing non-value-added tasks (transporting material between cutting and layup steps, rolling and unrolling the material to cut and transport) by consolidating separate tasks into one repeatable step.

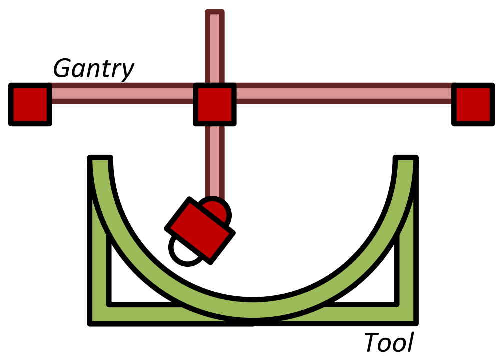


Figure 129: Automated reinforcement layup concept 1: Basic ATL

Concept 2: Ply cutter + roller pick and place

Figure 130 presents a concept that combines a CNC ply cutter (Assyst Bullmer, 2020) with a rolling end effector that can pick and place large plies (ARM Automation, 2018) (Loop Technology, 2020). This concept is very similar to the standard ATL concept, with the major difference being the separation of the ply cutting and layup tasks. Whilst this inevitably increases the number of tasks (and hence operational costs) it generally allows for greater flexibility and cutting functionality. The CNC ply cutter is able to provide more complex 2D ply shapes compared to an ATL device and can even be combined with vision systems to automatically generate ply shapes from photos, reducing operational labour and material wastage (Autometrix, 2020). Whilst the rolling end effector can pick up a wide range of 2D shapes, it is limited in 3D drapability functionality just as the ATL.

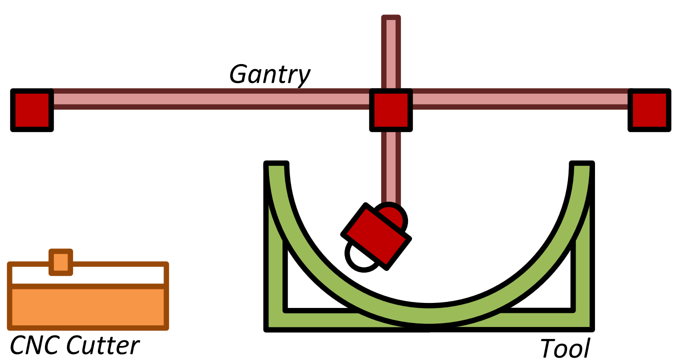


Figure 130: Automated reinforcement layup concept 2: Ply cutter + roller pick and place

Concept 3: Ply cutter + needle gripper pick and place

Figure 131 presents a concept that is very similar to concept 2, however the rolling end effector is replaced with a needle gripper end effector (Schmalz, 2020). Needle grippers are selected over vacuum grippers as they are considered to be a more robust solution for this case study. Even so, handling large plies with this technology is challenging due to the weight and drapeability of each ply. Moving plies from the cutter to the tool using this method leaves the plies somewhat exposed as they are not rolled or contained. There is also a risk of one or more grippers failing, which could cause the end effector to drop the ply.

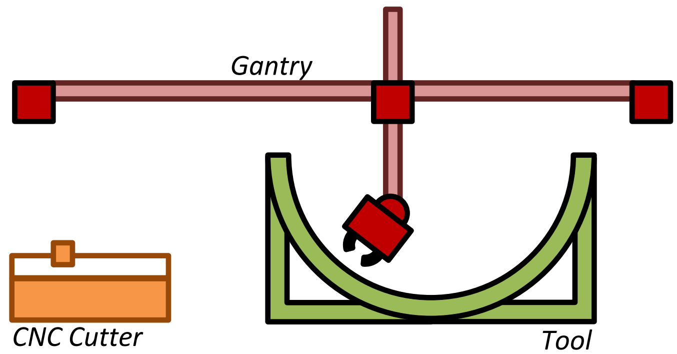


Figure 131: Automated reinforcement layup concept 3: Ply cutter + needle gripper pick & place

Evaluation of concepts

Table 45 highlights the strengths and weaknesses of each concept and indicates that concept 1 (ATL) is the most suitable option for automated reinforcement layup. A rolling layup mechanism was previously developed to manually deposit wide tapes onto the tool in chapter 5. The fundamental idea of rolling reinforcement onto the tool is not changed as this appears to be the most effective method for laying up the long, continuous fibres that are required throughout the hull shell structure.

ATL offers faster deposition rates and greater process flexibility and is generally a more robust and widely available technology compared to other concepts. The main disadvantage of this concept is the limitation on ply shapes and local details; however, this is not a major concern for the simplified hull shell due to its simple layup and construction. Future modifications may be required to accommodate the complex geometries around the bow and stern. ATL is therefore taken forward as the main reinforcement layup method, and the concept is developed further when combined with the infusion process in a later section.

Table 45: Evaluation matrix for automated layup concepts.

	Concept 1	Concept 2	Concept 3
	ATL	**Ply cutter + Roller P&P**	**Ply cutter + Vacuum Gripper P&P**
Range of geometries, shapes and local details.	This scheme will struggle with complex double curved geometries. Cutting functionality can be built into the ATL head, enabling layup of rectangular and trapezoidal shapes. Narrower tapes could be used for local details, but this may require interchangeable end effectors.	This scheme is generally limited to flat and single curvatures due to the rolling end effector. Use of a CNC cutter allows for more complex 2D ply shapes to be made.	Additional functionality can be built into the end effector to manipulate the ply in 3D space. Plies can therefore conform to a range of tool geometries. Use of a CNC cutter allows for more complex 2D ply shapes to be made.
Maximum ply size	Ply size is limited to the width and length of roll, allowing for very large plies to be produced.	Large ply cutters are available with conveyor belt beds that can produce plies up to the maximum length of the roll.	Typically limited to small/medium sized plies. Handling larger plies requires very heavy and complex end effectors with many grippers.
Process flexibility and upscaling	ATL path must be reprogrammed to accommodate any modifications to tool geometry or layup. Existing end effector would be applicable to large structures, although the gantry may need to be expanded to accommodate larger structures.	A larger ply cutter may be required to supply larger plies to reduce layup time. Existing end effector would be applicable to large structures, although the gantry may need to be expanded to accommodate larger structures.	Difficult to accommodate larger plies, so creating larger structures will take much longer due to increased number of layup steps. The gantry may also need to be expanded to accommodate larger structures.
Risk of process failure	ATL technology is fairly mature. Progressively rolling material onto tool with adhesive backing and uniform compaction will minimise risk of plies peeling away from tooling.	This concept is similar to ATL. Progressively rolling material onto tool with adhesive backing and uniform compaction will minimise risk of plies peeling away from tooling.	Handling and moving heavy, drapeable plies in the factory may risk the reinforcement separating from one or more grippers. This could cause the ply to be dropped and/or damaged.
Ease of installation	A single ATL device must be setup and the tool path programmed.	Two key pieces of automation equipment must be setup. And integrated together. The CNC cutter is an off-the-shelf piece of kit, and therefore fairly simple to setup. Setup of the pick and place system is more complex.	
Deposition rate	Material is directly deposited into the tool via a single step. Deposition rate is therefore predicted to be faster than alternative options.	Deposition rate potentially slower than ATL due to cutting and layup stages being separated. The pick and place head must refill after each ply laid up on the tool, so entire layup process will take a long time.	
CAPEX	Gantry + ATL + laser tracker	Gantry + CNC cutter + pick and place	Gantry + CNC cutter + pick and place
OPEX	Opex low compared to manual process. Average deposition rate combined with average level of process flexibility leads to average OPEX compared to other concepts.	Opex low compared to manual process. Slow deposition rate combined with average level of process flexibility leads to higher OPEX compared to concept 1.	Opex low compared to manual process. Slow deposition rate combined with low level of process flexibility leads to higher OPEX compared to concept 1 and 2.
Effect on structural performance	Continuous fibres throughout the structure are possible using this concept, maximising the structural potential of the material.	CNC ply cutter can only create plies of certain size and width, therefore overlapping of plies will be required to produce a continuous structure. It is thought that this would have minimal effect on structural properties due to the large plies and fewer overlaps.	Smaller plies will result in more overlaps, reducing the structural efficiency of the laminate.
Total score	22	20	15

6.2.1.5 Foam core layup

A cable bot system with an integrated foam pick and place end effector would be the most suitable option due to the low weight of the foam and large working envelope required. The end effector would have an additional rotational degree of freedom to match the curvature of the tool. This section focuses on a identifying a suitable type of gripper to pick up the foam sheets.

Concept 1: Vacuum gripper

Foam sheets are lifted at several positions using end effectors that apply vacuum suction (Loop Technology, 2020). This allows the part to be picked up with access to only the top surface. The rubber vacuum seals that are used to create this suction are most effective when applied to flat, smooth surfaces. The closed cell foam core material has a rough surface and will be thermoformed to a variety of curved shapes, so the vacuum seals may not be reliable for picking up these foam panels.

Concept 2: Needle gripper

In this process several small needle-like grippers are pushed into the top surface of the foam panel to create a mechanical lock between the panel and the end effector (Schmalz, 2020). This process creates small holes in the foam panel when the needles are removed. For some applications this could be considered unacceptable damage, however the foam panels used in this structure already feature through-thickness perforations, so some additional holes in the surface are not thought to be an issue. As with the vacuum gripper, this process can be used to pick up objects by contacting only the top surface. Machine vision and force-feedback systems could be implemented to correctly position the end effector against the foam panels and activate the grippers.

Concept 3: Mechanical gripper

This process aims to replicate the manual process of lifting foam panels onto the tool by mechanically supporting several points along the edges of the object. Mechanical clamps grip the foam panel at multiple positions to provide a robust grip whilst creating minimal damage (OnRobot, 2020). This is a more complex procedure compared to the vacuum and needle grippers and will require sophisticated grippers with several integrated sensors to correctly position each clamp on the foam panel. Furthermore, access to all sides of the foam panel is required, so laying foam panels flush against adjacent panels on the preform may be difficult.

Evaluation of concepts

The needle gripper appears to be the simplest and most effective solutions for this application. The vacuum gripper does not appear to be very robust solution for this application, and the mechanical gripper would likely be too complex and expensive. The needle gripper allows a range of different shaped foam panels to be picked up using a relatively simple and affordable method. The main disadvantage of this scheme; the resulting holes left by the needles, is not a critical issue for this application. The compatibility of this approach with the selected materials would need to be verified through physical trials.

6.2.1.6 Vacuum bagging

Vacuum bagging has evolved over the years to accommodate the manufacture of high-performance composite structures such as aircraft components and tidal turbine blades. The development of the bagging materials and process is based upon a heavily manual process which is difficult to replicate with robotic equipment. Alternatively, the materials and process could be redesigned to accommodate automation. These two contrasting approaches are discussed in further detail below:

Concept 1: Automated disposable bagging procedure

Whilst difficult, it should be possible to deposit tacky tape and vacuum bag using an ATL technology similar to that which was selected for the reinforcement layup. Various pick and place systems with integrated machine vision could be used to position a number of consumable items onto the perform such as resin feeds and outlet tubes. Attachment of spiral/infusion tubes to various connectors would be difficult to automate due to the dextrous nature of these tasks. Whilst technically possible, the development cost and time related to such a device would be great.

Concept 2: Re-usable custom vacuum bag

Re-usable silicone vacuum bags can be created and moulded to the required geometry (Alan Harper Composites, 2020) (Smooth-On, 2019) (Silicone Composites, 2019). The creation of the silicone bag via spraying can be automated fairly easily with a robotic arm, however a technician may be required to help define additional details such as resin feeds and vacuum outlets. After the bag has been produced, it can be placed onto the tool using a robotic arm or gantry. The re-usable bag eliminates the need for consumables such as tacky tape and spiral tubes, meaning that the only repeatable actions required during production are the positioning of the bag on the tool and the subsequent removal after infusion and cure. These reusable bags have been demonstrated on small/medium sized parts in industry. No evidence has been found of this technology being applied to tools of the scale of the hull shell. Potential practical issues such as handling and positioning such a large bag would need to be investigated further.

Evaluation of concepts

The current vacuum bagging procedure has evolved over the years as a manual process and is therefore not very compatible with automation. The re-usable silicone bag is the most compatible option for automation as it consolidates multiple complex processing steps into a single, simple action, and results in fewer technical challenges compared to automating the conventional bagging approach.

6.2.1.7 Infusion

Resin injection machines are currently the most commercially feasible option for automating resin delivery into a preform. It is therefore assumed that an injection machine will be implemented into the automated infusion process. Dielectric resin flow sensors can also be embedded into the tooling to monitor resin flow front progression and degree of cure (Infactory Solutions, 2019) (Synthesites, 2019). These sensors can provide control feedback to the injection machine, enabling a fully automated resin injection process. The potential of dielectric flow sensors has been demonstrated within the Ecomise research project (Composites World, 2020) (European Commission, 2016). However, these sensors are expensive and may not be a commercially feasible option for larger parts where several hundreds of sensors may be required. A camera mounted above the infusion is more affordable alternative for measuring flow front progression, provided that a transparent vacuum bag is used. This method can measure the flow front speed and shape to a much higher resolution than discrete sensors. However, a camera can only provide information of the flow front on the bag surface, and so may not be as applicable for thicker parts where resin flow deep within the preform can be complex and somewhat unpredictable.

This section focuses on the compatibility of different infusion strategies with these automated infusion technologies. Three contrasting options are discussed: one-shot infusion, large section infusion and modular panel infusion. These concepts are evaluated against the following criteria:

- **Risk of process failure:** There are multiple variables that can affect the infusion process and potentially cause issues or process failure. The total raw materials cost for a 75m long hull shell is estimated at 800k Euro. Therefore, the risk of process failure is an important factor to consider. The additional challenge of vertical infusion may further increase the risk of process failure.
- **Process time:** This is a comparative estimate for how long it will take to produce a 75m hull shell. The addition of extra processing steps will likely increase the total process time.
- **Quality/process control.** This describes how effective each option is at delivering the required tolerances and meeting the customer specifications. At this stage, it is difficult to go into depth with quantitative analysis, therefore only a qualitative discussion is presented.
- **Process flexibility and upscaling.** Future modifications or improvements to the product design are a possibility. A greater level of flexibility within the process will accommodate product variations at a lower cost and reduced equipment downtime. The current trend is to manufacture progressively larger ships out of composite materials. It is reasonable to believe this trend will continue, so the chosen manufacturing process should be up scalable to accommodate larger ships hulls in the future.

- **Compatibility with a shipyard environment:** Infusion processes are not typically done at this scale within a shipyard. This is a measure of how much change is required within the shipyard to accommodate the production of the hull shell.
- **Ease of installation:** One major barrier to entry for automation technology is the time, cost and complexity related to setting up systems in the end-user's factory or shipyard. This includes additional infrastructure, training and change of practices that must be implemented to effectively utilise the automation equipment. The shipyard may also wish to modify or move the process line and making this process easier could be a selling point. A "Plug and play" design philosophy could be considered.
- **Ease of maintenance:** This is also of relevance to the end user. A simple, off-the-shelf product could be operated and maintained by the end user, and obvious selling point for the customer.
- **CAPEX:** A comparison between estimated capital expenditure of each concept.
- **OPEX:** It is predicted that the operational costs for these automated concepts will be lower than equivalent manual processes. However, there may be variations in OPEX between the automated concepts due to the number of processes/equipment required.
- **Effect on mechanical performance:** Some concepts will feature modifications to the overall hull design which may affect the global strength and stiffness of the structure.

Concept 1: One-shot infusion

This is the strategy described in chapter 5, infusing the 75m hull shell in one shot. As this concept features only a single bagging and infusion stage, it is expected that process time and operational costs should be lower than the alternative concepts. However, the infusion stage is complex and prone to variations due to material preparation, layup tolerances and vacuum bag integrity. The monetary value of the materials on the 75m tool would exceed 800k Euro, and the risk of scrapping it all due to a process fault is simply unfeasible. Re-work and repair may be feasible depending on the scale of the defect; however, this would likely lead to less-than-optimal properties and additional processing costs.

Monitoring equipment such as embedded flow sensors and cameras/vision systems mounted above the tool could be implemented to provide a control feedback loop. Due to the sheer scale of the tooling, this would be expensive to setup and maintain as thousands of sensors would be required. Implementation of this concept would require many technical and commercial challenges to be overcome. However, the key advantage of this process is that it fully exploits the advantages of composite materials, creating a single, continuous structure with no joints or seams.

Concept 2: Large section infusion

This concept aims to reduce the risk associated with infusing a hull shell in one-shot by dividing the hull into large symmetric sections along the 75m length, which are infused separately and bonded together. The additional bond lines throughout the hull shell will reduce the structural efficiency of the overall hull shell structure, however positioning these joints at the connections between the bulkheads and shell could reduce this effect. This concept does not eliminate key process challenges such as vertical layup and infusion, however the smaller scale allows for more manageable bagging procedures and reduced consequence of process failure. It is expected that this concept will result in greater total process time and operational costs as the number of bagging and infusion steps are increased, together with the addition of subsequent bonding operations.

Concept 3: Modular panel infusion

This approach aims to further reduce the risk associated with infusing the hull by splitting the structure into a number of even smaller, modular panels that are bonded together after cure. The obvious limitation with this scheme is the effect on structural performance due to the addition of large bond-lines throughout the hull shell structure. This would need to be evaluated by the ship design authority to fully understand the effect on performance and weight. To minimise the negative effect on structural properties, it is proposed that the hull shell be split into panels that fit within the existing framework created by the deck and bulkhead assembly (Figure 132). This means that the additional shell bond-lines are supported by the ends of the decks and bulkheads. This should also streamline the overall hull assembly process, as the bond-lines in the shell are located at the shell-deck and shell-bulkhead joints. In this report the bulkhead spacing is assumed to be 6m, so the modular panels are 6x3m in size.

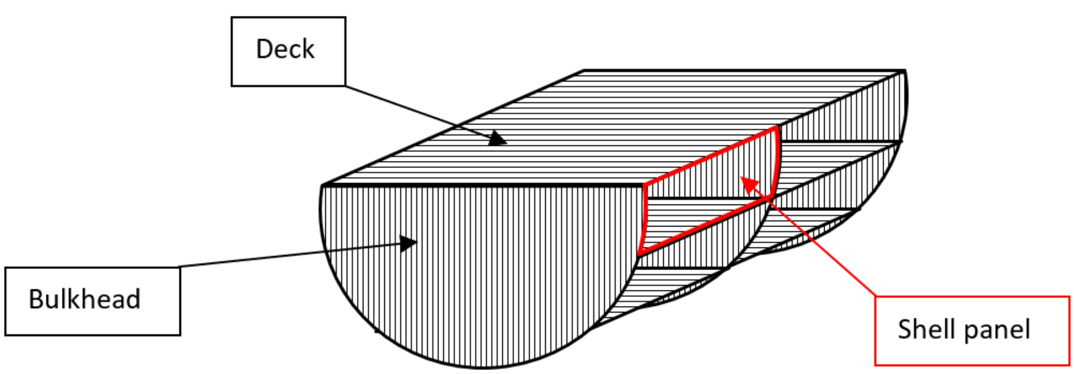


Figure 132: Modular panel assembly concept

Quality assurance of large, bonded sections within a shipyard environment is also an area of concern and would require further research and development. However, the production of the entire ship hull (including decks and bulkheads) features some significant bonding operations already, so it is not thought that this proposal is unfeasible. Alternatively, the panels could be assembled in a semi-cured state and co-infused (resin infused along the panel bond-lines) and co-cured to produce a continuous structure without adhesive. These panels could also be designed to interlock with one-another, creating additional mechanical locking throughout the structure. Regardless of the assembly details, this modular proposal appears to offer a good overall compromise, enabling a much simpler layup, bagging, and infusion processes at the expense of an additional assembly operation.

Infusion of smaller panels greatly reduces the risk and consequence of a process failure, and completely removes the challenge of a vertical infusion. The infusion of smaller parts also means that fewer embedded sensors and vision systems are required to monitor and control the process, further reducing capital and maintenance costs. It is also much easier and more cost effective to build a clean room or controlled environment around the infusion of smaller panels compared to a 75m long hull. This proposal allows the infusion stage to be isolated from the general shipyard environment, allowing easier implementation of an infusion process within a typical shipyard environment. Finally, as this proposal features a series of simpler repetitive steps, it is more compatible with automated technologies compared to the single complex task of infusing the full hull in one-shot.

Evaluation of concepts

The three infusion concepts are evaluated in Table 46 against the previously defined criteria. The modular approach is identified as the most suitable concept as it significantly reduces commercial risk whilst providing sufficient process time and good flexibility. This concept also complements the modular preform and reusable vacuum bagging concepts that were previously proposed. The hull design modifications that are required to accommodate this panel assembly concept are left as future work.

For the purposes of this case study, adhesive bonding has been selected as the method for assembling the hull shell modules as this process will be used to assemble the decks and bulkheads. Further process development is required to identify methods for bonding large-scale structures with sufficient quality and control. Alternatively, co-infusing semi-cured modular panels by injecting resin into small gaps between panels may be a suitable solution to improve the quality of the assembled structure. This could be implemented with a mechanically locking design to create a joint that is sufficiently strong and of sufficient quality. Development of this alternate assembly method is left for future work.

Table 46: Evaluation matrix for infusion concepts.

	Concept 1	Concept 2	Concept 3
	One-shot	**Sectional**	**Modular**
Risk of process failure	Increased risk of failure due to large, complex infusion with vertical sections. Consequence of failure is high due to large quantity of material being infused in one go.	Same risk of failure as concept 1 due to scale and vertical sections. Reduced consequence of failure due to smaller sections being infused.	Low risk of process failure due to smaller, simpler, horizontal infusions of panels. Low consequence of failure due to much lower quantities of materials being infused at one time.
Process time	Potentially shorter process time compared concepts 2 and 3 as only a single bagging and infusion step is required.	Longer process time as additional bonding steps are required to create the hull shell. Movement and bonding of such large sections could be challenging.	Longer process time as additional bonding steps are required to create the hull shell. Handling and bonding smaller panels is easier than larger sections, but more bonding steps.
Process control	Large total tool surface area means it is very expensive to setup and maintain embedded flow sensors throughout. Multiple cameras required to monitor flow progression on bag surface.		Small tool surface area means is it relatively affordable to setup and maintain embedded flow sensors and mounted camera.
Process flexibility and upscaling	Highly inflexible process due to single fixed tool geometry. Modifications and upscaling will require new tooling.	This concept shares the same limitations with concept 1 as the geometries of the large sections are fixed.	A range of modular panels can be manufactured to form a range of different hull shapes and sizes. An assembly rig will be required for each different design; but this is cheaper to setup than new tooling.
Compatibility with shipyard environment	The part is laid up and infused on the 75m tool in the shipyard. To accommodate this the environment must be somewhat controlled (temperature, wind, contaminants) and additional facilities such as raw material storage and handling and vacuum bagging stations must be added.	This concept shares the same limitations as concept 1 due to the scale of the parts. It may be possible to isolate a small area of the shipyard for infusion and move the tool sections into this area when required. However, this process will likely be time consuming and costly.	Due to the modularisation of the structure, it is possible to separate the panel manufacture from the general shipyard and setup an isolated composite panel manufacturing booth in which the air quality and temperature is controlled. Furthermore, the panel manufacture could be done off-site. Some modifications to the shipyard would be required to accommodate the bonding assembly stage.
Ease of installation	Very large tool would need to be manufactured and installed. Infusion machine and bagging equipment would also need to be installed and integrated into the custom tooling.	Large tooling sections would need to be manufactured and installed. Infusion machine and bagging equipment would also need to be installed and integrated into the custom tooling.	Panel manufacture area can be installed as a single product. Integration with existing shipyard is minimal. Existing gantry infrastructure can be used to move and assemble panels. A large bonding rig would need to be assembled.
Ease of maintenance	Large tooling would require significant maintenance operations (tool prep etc.) to ensure good vacuum integrity and release. Multiple infusion machines would need maintenance which can be performed by a trained employee or outsourced to the machine supplier.		Panel manufacture area houses a more compact infusion and bagging operation that can simplify maintenance procedures. Smaller, but more complex tooling would also need maintenance.
CAPEX	Full tooling for each bespoke hull design is costly. Multiple infusion machines are required alongside large-scale bagging equipment.		Panel manufacture area is flexible and can be used for a range of hull designs. This reduces CAPEX for individual products.
OPEX	Single infusion process, relatively fast process time but average maintenance and capital costs.	Multiple infusion steps increase bagging and infusion costs. Average process time combined with average maintenance and capital costs.	Multiple infusion steps increase bagging and infusion costs. Average process time combined with average maintenance costs and low CAPEX.
Effect on structural performance	The hull is manufactured in one continuous section. There are no local discontinuities or weaknesses.	Bonded large sections may lead to a slight reduction in global strength and/or stiffness.	Bonded panel assembly would lead to a reduction in global mechanical properties due to large volume of bond-lines.
Total score	19	17	24

6.2.1.8 *Cure and post-cure*

After infusion the preform is left to cure for a predefined duration depending on the resin, accelerator and peroxide mix ratios. This normally takes 24 hours and can be done at room temperature. Basic temperature control equipment found in a typical shipyard are sufficient for this step.

To achieve optimum resin properties the structure must also be post-cured for 2-4 hours at 50-60°C. Shipyards do not have the facilities to reach these temperatures, so additional equipment will be required to achieve this post-curing step. A post-cure may also be required after assembly to achieve optimum adhesive properties. Four concepts are considered ranging from general to localised heating, and are evaluated against the following criteria:

- **CAPEX:** Initial investment required to install post-curing facilities within the shipyard.
- **OPEX:** Operational costs associated with heating the hull.
- **Compatibility with shipyard environment:** Disruption caused by installation/operation of equipment.
- **Process time:** The time taken to apply the post-cure.
- **Uniformity of heating:** The quality of the post-cure as determined by the temperature distribution throughout the hull shell.

Concept 1: Heated building

There are some examples of composite shipyards heating the entire workspace. For example, Royal Huissman have 7 heated halls with clean, controlled environments for constructing and assembling their composite vessels (Royal Huisman, 2018). The costs associated with this expansive infrastructure is expected to be very high. For the purposes of applying a moderate post-cure, this option is expected to incur higher operation costs due to the greater volume that must be heated. However, conducting the layup, assembly and post-curing operations within the same location saves time and space, as the vessel does not need to be moved to a dedicated post-curing oven.

Concept 2: Dedicated oven

A separate oven could be installed alongside the production line. This option would be very expensive to setup, although the heating step is expected to be more efficient than concept 1 due to the smaller volume. Moving the hull in and out of the oven may be challenging and increase the total process time.

Concept 3: Heated tooling

Electrical or fluid heating elements can be installed on the backside of the tool surface to provide heating (and cooling in the case of fluid systems). This is a more cost-efficient way of heating the hull and can be easily incorporated within the production line. However, as the heating is only applied to the outer side of the hull shell, a temperature gradient is created meaning that different areas of the structure are post-cured at different temperatures. Insulation could be incorporated into the tool to reduce heat loss.

Concept 4: Localised heating

Instead of heating the entire building, an insulation barrier can be created around the hull shell to create a closed volume that can be heated. This concept uses the same air heating method as concept 1 but is far more efficient due to the reduced volume of heated air. Insulation panels can be built into the tool/assembly rig so that the only additional process step required is lowering an insulating lid down onto the top of the hull using a gantry.

6.2.1.8.1 Evaluation of concepts

The four concepts are evaluated in Table 47 against the previously defined criteria. Table 47 indicates that concept 4 is the most suitable as it provides the lowest overall cost and processing time and minimal disruption to the shipyard operations.

6.2.1.9 Demoulding

Two demoulding stages are identified based upon the previously defined manufacturing steps. The first demoulding stage concerns the separation of modular panels from the reconfigurable tool. As the panels are very stiff and of gradual curvatures, they should be relatively easy to demould without risk of damage. Dedicated lifting points are built into the corners of the panels to further support the demoulding process.

Peeling motion is an efficient method for separating a cured part from a tool. It is proposed that this peeling action is provided by the reconfigurable tool; progressively changing its shape whilst the sandwich panel is held in place. It is sufficient to grip the sandwich panel on the four lifting points using a dedicated end effector. After the panel has been separated from the tool surface it must be transported away from the tool. In the proposed manufacturing concept, the panels are taken directly from the demoulding tool to the assembly rig via an overhead gantry. Therefore, it is proposed that the dedicated end effector that is used to hold and transport the panel during demoulding is integrated into the overhead gantry rather than the robotic arm. This minimises non-value-added time linked to moving panels around the factory.

The second demoulding stage concerns the separation of the assembled ship hull from the assembly rig. To facilitate the demoulding process, the assembly rig shall be constructed in modules so that it can be subsequently disassembled around the finished ship at the end of production. Further refinement of both demoulding stages is left for future work.

Table 47: Evaluation matrix for post-curing concepts.

	Concept 1	Concept 2	Concept 3	Concept 4
	Heated building	**Dedicated oven**	**Heated tool/assembly rig**	**Localised heating**
CAPEX	Air heating equipment is quite affordable. A number of these heaters would need to be strategically placed throughout the building.	A separate 15x10x75m oven will be extremely expensive to setup.	Electrical/fluid heating systems are fairly expensive to install due to the size of the tooling. Insulation panels would also be required to minimise heat loss.	Air heating equipment is quite affordable. Additional insulation panels would be required; however, these are quite affordable.
OPEX	It will be very expensive to heat the entire building for 2-4 hours each production cycle.	Heating costs are low due to the reduced volume of heated air.	Efficient localised heating results in reduced operational costs.	
Compatibility with shipyard environment	Heating the entire workspace will restrict any other operations within that building.	The oven will take up a significant area within the shipyard. Moving the hull in and out of the oven would also be challenging and could be disruptive to other operations.	Minimal impact on the production line and general shipyard environment as heating is applied locally to the hull without moving the tool or causing disruption.	
Process time	It will take a long time to heat the entire workplace up to 50/60°C.	The heating time is reduced due to the smaller volume of heated air, however moving the hull in and out of the oven would add to the process time.	Heat is applied directly to the tool, resulting in a much quicker heating process (conduction). However, heating is only applied to the outer face, which could slow the process down. The heating procedure can be conducted directly on the production line, eliminating the need to move the tool.	The heating time is reduced due to the smaller volume of heated air. The heating procedure can be conducted directly on the production line, eliminating the need to move the tool. The insulating lid must be lowered onto the tool, which adds to the total process time.
Uniformity of heating	The air around the hull is heated to a uniform temperature, however there may be a temperature gradient through-thickness.		Heat is directly applied to one side of the hull, creating a strong temperature gradient through-thickness.	The air around the hull is heated to a uniform temperature, however there may be a temperature gradient through-thickness.
Total score	8	9	12	14

6.2.1.10 *Finishing*

Automated robots arms have been used in the automotive industry for many years to conduct various drilling, machining, painting and finishing operations. This technology is ideal for these complex tasks as the robot arms offer additional degrees of freedom compared to gantry or cable bot systems.

A detailed automation concept is not proposed for this process step as it falls outside the scope of the demonstrator production. A robotic arm mounted onto a gantry rail would be the simplest solution, providing sufficient degrees of freedom and working envelope to perform the machining and finishing tasks. A series of interchangeable end effectors would allow a range of different machining operations to be performed. Further development of this idea is left as future work.

6.2.2 Proposed concept for an automated manufacturing process

In this section the individual concepts for each process steps are integrated together to form an automated production line concept. A summary and process flow chart (Figure 134) is presented below.

This manufacturing concept reduces the risk associated with infusing a 75m hull in one-shot by dividing the structure into a number of **modular panels** (6x3m). The manufacturing concept therefore describes a process for manufacturing smaller panels that are later **bonded together to form the hull shell structure**. The bonds between the panels are located along the deck and bulkhead bond-lines to reduce their negative effect on structural mechanical performance.

A **gantry system** is installed for general shipyard tasks, spanning over the entire workspace and providing a facility to **transport a wide range of objects** of different sizes and weights, from rolls of reinforcement to sections of the assembly rig. A smaller **cable bot system** is installed locally to **move foam and glass reinforcement** from storage to the panel manufacturing station. **The panel manufacturing station** consists of a **foam thermoforming bay**, **a robot mounted ATL**, **a reconfigurable panel tool** and **an infusion module**. This panel manufacturing station is isolated from the general shipyard environment to better control air quality, temperature, and relative humidity. Foam panels are supplied as flat sheets of 1x2m area. Within the **thermoforming bay** these panels are **shaped under high temperatures to match the hull curvature** using a **reconfigurable thermoforming tool** of a similar size. A unique barcode is printed on each foam sheet to indicate what panel they correspond to, and where within that preform they should be laid up. The foam sheets are then **sorted into kits** ready for layup. **A robot mounted ATL** device deposits plies of glass reinforcement into the **reconfigurable panel tool.** The same robot arm can swap to **a foam pick and place end effector** to place the thermoformed foam sheets onto the layup when required.

The infusion module is activated after the preform layup is completed. The robot arm swaps to a third end effector that can **pick and place the reusable vacuum bag** over the preform. This bag contains all the necessary features such as inlet and outlet ports, internal resin feeds and a perimeter seal. The vacuum line and resin feed line are attached to the bag automatically using the robot arm. **Infusion parameters such as temperature and humidity are recorded** prior to resin injection. **Several embedded flow sensors within the reconfigurable panel tool** are used together with **an overhead mounted camera** to monitor the infusion process and feed data to the **centralised control system**. This control system comprises of various integrated sensors and software packages and is discussed in further detail in the following section of this report. After the infusion is complete, heat is applied to the part to accelerate cure using local heaters. The vac bag is removed, and the panel is **demoulded by the robot arm**. A unique barcode is printed on the panel for identification, before it is taken away by the **overhead gantry** to an intermediate storage/kitting area ready for assembly.

The panels are positioned onto the assembly rig by the gantry; their location determined by their unique barcode. **An adhesive application nozzle** is installed onto the gantry to apply adhesive prior to **joining the panels**. At this stage, the **decks and bulkheads** are also **bonded to the hull shell assembly**. After the assembly has been completed a **post-cure** is conducted at 60°C for 2 hours. This is done by locally heating the air around the assembly. Insulation is pre-built into the assembly rig to minimise heat loss. A large insulating lid is lowered onto the top of the hull to provide a sealed volume. **Hot air** is then pumped into the sealed volume to provide the post-cure for both the infused panels and the adhesive bonds. Internal **thermocouples** are installed throughout the assembly rig to provide a **closed loop control system**. After post-cure, the assembly rig can be used to support the hull whilst the superstructure is added. The assembly rig is then dismantled to reveal the finished vessel. **Painting and finishing procedures** are then conducted by **gantry mounted robots**.

6.3 Concept for an automated composite tidal turbine blade manufacturing process

This section briefly explores a suitable automated manufacturing method for producing large composite tidal turbine blades. Chapter 1 introduced this case study alongside the composite ship hull, however due to the limited project duration, a detailed process development study could only be conducted for one case study. The intention of this section is to demonstrate that the solutions developed and presented in the previous chapters can be applied to other large-scale marine structures such as tidal turbine blades. Therefore, the manufacturing concept generated in this section will be based upon solutions developed in previous chapters of this thesis.

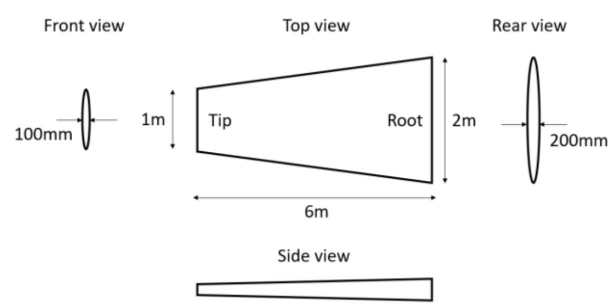


Figure 133: Tidal turbine blade geometry

Figure 133 shows the simplified geometry for a 6m long, 2m wide, fully monolithic tidal turbine blade that is representative of the case study selected in Chapter 1. It is important to note that the geometry shown in Figure 133 represents a generalised design and does not represent a specific commercial product. This generalised geometry is included in this report to help the reader understand and appreciate the manufacturing challenges.

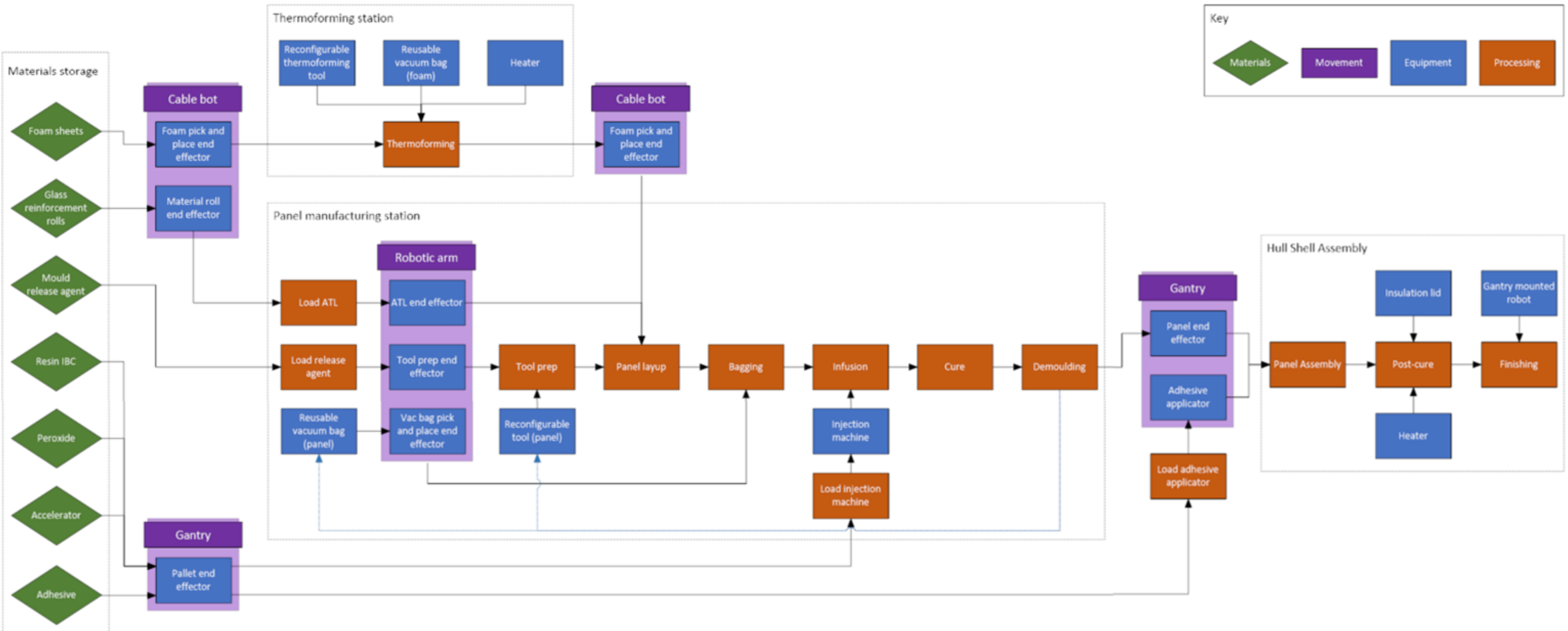


Figure 134: Proposed automated hull manufacture process flow chart

The blade acts as a cantilever beam that is fixed to the rotor hub at the blade root. Maximum shear stresses and tensile/compressive stresses assumed to be at the mid-thickness plane and outer surfaces, respectively. A simplified list of requirements is provided below for this case study. These have been generated based upon the hull shell requirements and the author's experience and involvement in commercial tidal turbine blade projects. These requirements directly relate to the top-level manufacturing details outlined above and are included in this section to help guide the development of a suitable manufacturing concept.

- **Surface Quality:** The blade is a hydrodynamic structure, so all external blade surfaces must have class A surface finish. A rigid tool surface is therefore required to form the blade outer surfaces.
- **Materials and layup:** Glass fibre reinforcement and marine-grade vinyl ester resin is selected for this application based on cost and mechanical performance needs. For processes featuring ply layup procedures, a tailored 1200gsm quadaxial reinforcement should be used with a higher proportion of 0° fibres to support bending loads along the blade length. Continuous plies spanning the entire 2x6m blade area could be used, with the 0° fibre direction following the blade span (root to tip).
- **Fibre Weight Fraction and Laminate Quality:** In the absence of a specific project specification, the author will apply the quality requirements of the hull shell to this case study (see Section 3.2.1). This is thought to be a reasonable assumption based upon the similarities in material selection, monolithic construction, and operational environment.

6.3.1 Manufacturing process selection

A general manufacturing process concept must be selected prior to refinement and implementation of automated technologies. This selection process will follow the methodology presented in Chapter 3 for the hull shell case study. Several concepts are presented that describe potential top-level manufacturing approaches. These concepts were selected based on their suitability to the case study and ability to meet the requirements.

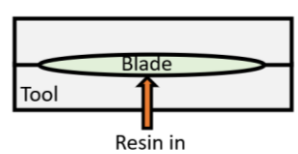


Figure 135: Tidal turbine blade RTM process

- **RTM:** A 2-part closed tool is used to inject resin into the dry preform in a single step. A 200mm thick monolithic laminate will have a high bulk factor and will therefore require high levels of force to close the tool.
- **Filament winding:** Fibres are wound around a central mandrel which spans the blade length and becomes part of the finished product. This mandrel could be made from steel (or other metal), or alternatively a pultruded composite feature which could minimise the effect

on structural properties. A design iteration would need to be conducted to incorporate this mandrel into the structural design. A finishing stage would likely be required to achieve the Class A surface finish required on all outer surfaces.

- **2-part infusion:** Applying the approach used for wind turbine blade manufacture, the blade is infused in two halves using open tooling and re-usable vacuum bags. The halves are then bonded together. The monolithic construction adds complexity to this process (compared to the hollow wind turbine blades) and requires a large bond-line across the entire blade span at the mid-thickness position.

These concepts are evaluated against the following criteria. The criteria were given equal weightings (1) for this initial evaluation activity.

Figure 136: Tidal turbine blade 2-part infusion process

- **Cost:** A relative comparison of the setup and operational cost of each process based upon the resources and equipment required. Only the basic process elements are considered at this stage (i.e., no automation equipment, which is assumed to be consistent across all options).
- **Process duration:** Top-level estimates for process duration are made based upon number of process steps required.
- **Process complexity and risk:** A relative comparison of the technical and practical difficulty, and the likelihood and consequence of process failure.
- **Effect on structural performance:** A comparison of how each process effects the design of the blade and hence the structural performance.
- **Geometry and surface finish:** A relative comparison of how each process affects the quality and geometric accuracy of the surface finish.

Table 48 shows the evaluation of each concept against the criteria. Each concept displays a range of strengths and weaknesses, with RTM achieving the highest score due to its potential ability to produce a structurally optimised blade in a single injection stage. However, as with the composite hull shell case study, there are several technical challenges which must be overcome via experimentation and production trials. Resin shrinkage during the cure of the thick monolithic blade may result in a poor outer surface finish. Further investigations may be required to quantify this effect and identify practical solutions. Implementation of a central mandrel for filament winding and a central bond-line for the 2-stage infusion would also require further development.

These further process development activities are beyond the scope of this thesis. Further investigations are suggested using a similar process development approach that was presented in Chapters 3, 4 and 5 to identify the most appropriate manufacturing solution. The purpose of this section is to focus on the application of automated manufacturing technologies within a tidal turbine blade manufacturing process. In the absence of these further investigations, RTM is selected as it is the highest scoring solution. Furthermore, there are examples of similar products being manufactured using this process (Dowty, 2020) (Airborne, 2020) (Composites World, 2011). The RTM process is also more closely aligned with the infusion developments and solutions presented in this thesis, whereas the filament winding approach would require far greater levels of development that are beyond the scope of this brief concept generation activity.

Table 48: Tidal turbine manufacturing process selection

Criteria	**RTM**	**Filament winding**	**2-part infusion (bonded)**
Cost	High cost: A closed tool comprising of two halves with compaction functionality and a resin injection machine are required.	Medium cost: Filament winding (and potentially mandrel production) equipment required.	Medium cost: Two tools, a resin injection machine, and an assembly rig are required.
Process duration	Fast: Single-stage process to create a single, continuous part.	Long: Three-stage process to create a mandrel, wind fibres, and finish outer surfaces. Fibre winding could take a long time due to part thickness and size.	Long: Three-stage process featuring 2 blade infusion stages and 1 assembly stage.
Complexity and risk	Process has potential to be quite simple and repeatable once setup. Risk of resin race-tracking over tool surface during infusion due to potential layup variation and preform movement. Risk of poor surface finish on top side.	Process has potential to be quite simple and repeatable once setup.	High risk associated with bond-line quality. Bond is located at mid-plane where shear stress is maximum. Large surface area of bond, difficult to verify/control bond-line thickness and quality.
Effect on structural performance	No major seams or discontinuities within main structure, so minimal effect on structural performance.	Effect of mandrel should be investigated. Difficult to achieve 0° fibres aligned along blade length using selected winding direction. 0° fibres are preferred to resist cantilever bending loads.	Large bond-line through centre of structure which may affect structural performance.
Geometry and surface finish	Resin shrinkage combined with thick monolithic section and closed tooling may lead to poor surface finish on top surface.	Surface finishing stage may be required.	Surface finish is good. Each half is created separately, so resin shrinkage will only affect the "internal" bonded surface.
Total score	**11**	**10**	**8**

6.3.2 Automated Tool Preparation

All tool surfaces are thoroughly cleaned, and release agent applied using the automated concept presented in Section 6.2. The smaller size of the tidal turbine blade compared to the hull makes this automated tool preparation concept far more applicable to this case study. The blade geometry fits within a typical robot arm working envelope (if the robot is mounted on rails to span the 6m blade length) (KUKA, 2018). Vision systems can be mounted above the tool to monitor the process.

6.3.3 Automated Reinforcement layup

Table 45 in Section 6.2.1.4 presents an evaluation of different automated reinforcement layup concepts for the composite hull shell. ATL was identified as the highest scoring concept for the hull shell, and whilst the two case studies share many similarities, the ply geometries required to form the tidal turbine blade geometry presented in Figure 133 would be difficult to achieve using standard ATL solutions (due to varying ply widths along the span). A CNC cutter + rolling pick and place end effector was the second-highest scoring option in Table 45. This concept is identified as the most suitable solution for the tidal turbine blade as it can effectively manufacture, handle, and layup large, flat plies with varying lengths and widths. A rolling ply pick and place robot would then transfer the plies from the CNC cutting table onto the tool. The mostly flat geometry over the blade span would be compatible with the rolling pick and place solution, however slight curvatures at the leading and trailing edges may lead to the need for manual layup aid from skilled laminators.

6.3.4 Automated RTM

The RTM tool can be opened and closed using automated electric motors or hydraulic/pneumatic equipment. Unlike for the hull shell case study, no complex vacuum bagging tasks are required, which significantly simplifies the procedure.

The preform shall be infused in the in-plane direction from root to tip using an infusion scheme similar to that used for the hull shell monolithic keel (Sections 4.6 and 5.8). Due to the length of the blade and the infusion speed/duration findings presented in Chapter 4, it is believed that multiple resin inlets that span the blade width will be required on the top and bottom surfaces (approximately 0.5 to 1m apart over the 6m blade length). The automated infusion concept (with injection machine and dielectric resin flow sensors embedded in the tool surfaces) presented in Section 6.2.1.7 would be applicable for this application. These sensors can be distributed across the inside faces of the two tool surfaces to provide information on resin flow front position in real-time. These sensors cannot provide resin flow data for regions deep within the thick monolithic preform. Flow simulation software should therefore be applied to create a digital twin of the manufacturing process, providing validated resin flow predictions in real time and enabling a greater level of control over the process.

The RTM solution is highly compatible with the automation concepts presented in the previous section. The smaller size of the blade compared to the hull shell and the lack of complex bagging procedures results in fewer technical challenges that must be overcome.

6.3.5 Automated Post-cure

An evaluation of post-curing options for the composite hull shell is presented in Table 47. This evaluation is also mostly applicable to the tidal turbine case study as well. Based on this evaluation, a heated tool is selected for the following reasons:

- The tidal turbine blade is much smaller than the composite hull shell, therefore addressing one of the two key limitations of the heated tool concept in Table 47: high CAPEX due to part size.
- A closed tool applied that encompasses the tidal turbine blade. Heat can therefore be applied across all external surfaces, addressing the other limitation of heating tooling in Table 47: heat is only applied to one side of the part.

Incorporating these factors into the evaluation presented in Table 47 results in heated tooling being the highest scoring solution. A heated tool would be a cost-efficient and rapid post-curing technique for this case study as it is able to apply heat directly to the part. Alternatively, an oven could also be used if already available in the factory to reduce CAPEX, however this would require an additional process step to move the part into and out of an oven using automated technology. A heated tool solution would not require this, resulting in a far simpler solution and a smaller factory footprint. Both solutions can be preprogramed to provide a specific cure cycle, and thermocouples can be embedded within the tool to support a closed loop control feedback system. Cure modelling simulations could be applied as part of the digital twin to achieve a greater level of control over this process.

6.4 Integrating automated manufacturing solutions

There are no known examples of a fully automated production line with an integrated resin infusion process, representing a significant gap in the necessary technical capabilities. To properly integrate automated technology into a production line that is both autonomously controlled and robust, one must incorporate a digital framework to monitor and control the automated equipment. This framework may consist of various sensors, theoretical models and simulation packages. Such tools are a useful means for designing efficient manufacturing processes and can be used alongside working production lines to gain a greater understanding of how a wide range of process variables can impact production rates, part quality and cost.

Whilst there are currently no examples of fully automated resin infusion processes in industry, digital manufacturing technologies have been implemented in many other applications outside of the composites manufacturing industry. For example, automation has been applied extensively in the automotive industry, utilising a variety of digital systems and robotic hardware to rapidly assemble automobiles (Ersing, P., et al., 2015) (Audi, 2020) (BMW, 2020). Bosch have developed an automated production line to manufacture control circuit boards using integrated sensors and software (Bosch, 2020). This process features a series of robots that can conduct a range of automated manufacturing steps. The architecture of this automated manufacturing process can be thought of as a series of discrete modules, each with a particular function. A software module sends commands to each robotic hardware module that makes up the physical production line. Raw process information is collected via embedded sensors and sent to a data processing module that converts this information into useful process monitoring data. A user interface module (in the form of a tablet or computer) allows the staff to access and act on this data as necessary. Visualising the process as modules enables clear identification of the key generic stages of an automated manufacturing process:

- Input data in the form of robot commands and product features/details.
- Execution of automated task.
- Collection of relevant output data in the form of equipment movement/position data, equipment condition, cycle time, measurable process variables, and/or product details (dimensions, quality, photo, etc.)
- Conversion of raw process data into useful monitoring data.
- Presentation of monitoring data for human interaction and decision making, and/or automated decision making based upon measured output data.

These align with the key digitalisation activities identified in a recent report on the digitisation of the UK automotive industry (KPMG, 2017). Various technical solutions exist to help achieve these automated tasks. For example, Siemens have developed a product lifecycle development system that integrates product design and manufacturing data, which can be combined with a manufacturing execution system to provide automated process control. The software can also simulate the effects of design modifications on the process (Siemens, 2020). Siemens also offer software for creating digital twins of the production line (Siemens, 2020). A digital twin is digital representation or simulation of a physical entity (such as a production line) that is used to analyse its physical counterpart using real-world data. This technology can be used to investigate the effects of various process modifications, or to predict and plan for maintenance intervals and equipment down-time (Cimino, C., et al., 2019) (Audi, 2020). GE have implemented digital twin technology to optimise the operation of their wind farm and gas turbine (GE, 2020).

To facilitate flexibility in the manufacturing process, Radio Frequency Identification (RFID) chips can be fixed to the product that inform the manufacturing module of the specific product details/features and required manufacturing steps. These chips have been used by GKN and Audi to support automated manufacturing processes (KPMG, 2017) (SICK, 2018). Autonomous solutions may also be applied to increase efficiency and reduce costs of manually intensive logistical tasks such as stock control and transport of materials throughout the factory.

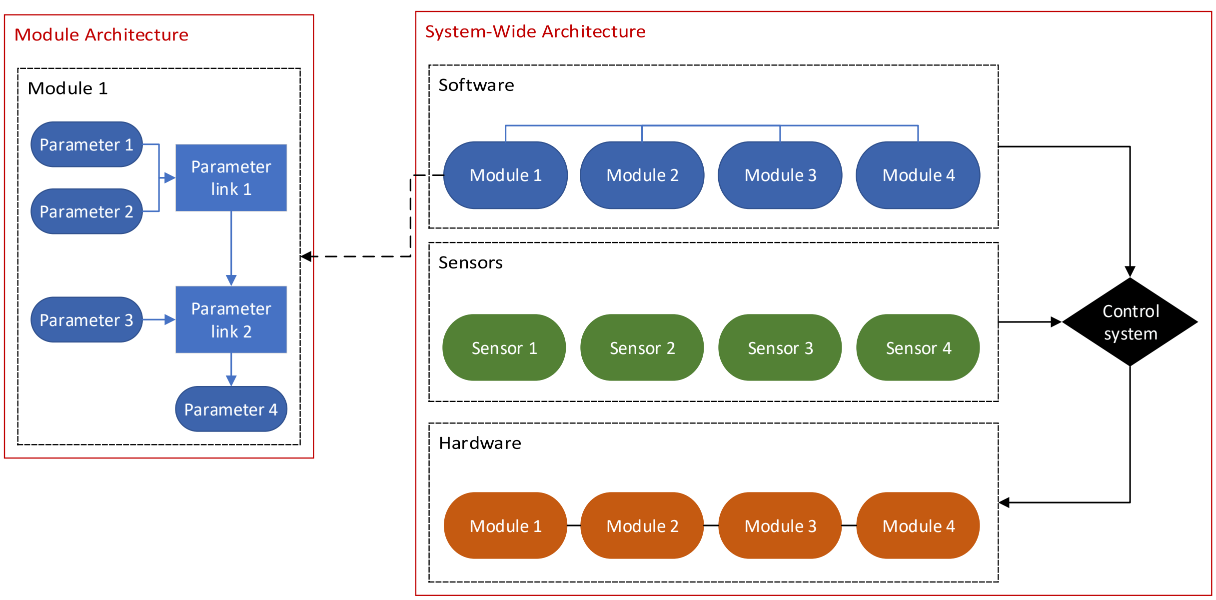


Figure 137: Example of module and system-wide architectures

The examples presented above show that commercial hardware and software solutions currently exist that can be integrated to generate a variety of automated manufacturing tasks. However, composite manufacturing processes can be highly complex with numerous material and process variables that must be considered. A thorough understanding of the process parameters must therefore be obtained to implement a digital framework into a composites production line. This ensures the correct data is extracted from the process and that a suitable control system architecture is implemented. In this section a basic methodology is presented for developing a digital framework that can measure, predict, and correct for variations in a resin infusion process. The key steps are:

1. Identifying relevant process parameters and their relationship to each other
   (e.g. temperature linked to resin viscosity)
2. Defining suitable procedures to measure, predict and control these parameters
   (e.g. embedded thermocouples linked to viscosity models)
3. Defining the process modules that describe the overall production line.
4. Creating separate flow diagrams that detail the architecture of individual process modules (such as the flow simulation module). This clearly shows both the inputs and outputs and the flow of data within each module.
5. Creating a system-wide architecture; integrating modules via a digital backbone
   (e.g. flow simulation module linked to a sensors package)

6.4.1.1 Identifying process parameters

To create such a system, one must first understand the link between all parameters, their individual and combined effect on the process and which ones can be measured and/or controlled. To do this, a methodology is proposed where process parameters are split into three categories: input, direct and output parameters. Input parameters, such as temperature, can be controlled and measured. They affect the process by influencing the direct parameters. Direct parameters, such as resin viscosity, directly affect the manufacturing process. These parameters can be measured prior to production but are difficult to directly monitor and control during the manufacturing process. Output parameters, such as the infusion duration, describe the outcome of the process. These are measured and compared against acceptance criteria to determine whether the manufacturing process is acceptable. Experimentation and simulation are useful tools for gaining a greater understanding of each parameter. Figure 138 outlines the relationship between each group of parameters and Table 49 presents the relevant parameters for a typical resin infusion process.

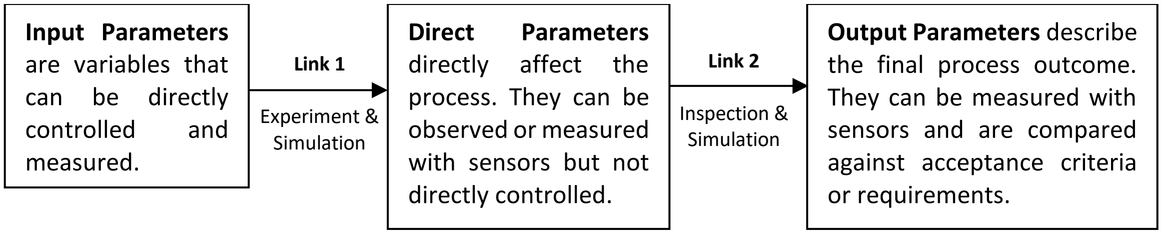


Figure 138: Relationship between process parameters for resin infusion.

Table 49: Relevant process parameters and the links between them for resin infusion.

Input Parameters *(Controlled)*	**Link 1**	**Direct Parameters** *(Measured)*	**Link 2**	**Output Parameters** *(Measured)*
Material handling/draping and layup	Permeability trials, layup and draping simulation	Reinforcement permeability	Flow modelling software	Flow front progression/infusion time. Voidage, geometrical accuracy, degree of cure.
Desired infusion strategy (inlet/outlet positioning)	Manufacturing variation/tolerance	Actual infusion strategy		
Resin temperature	Rheometer	Resin viscosity		
Resin/hardener mix ratio	Cure model (DSC)	Viscosity and gel time		
Desired vacuum level	Leak detection	Actual vacuum level		
Resin density, reinforcement areal weight	Infusion trial, calculation, material variation/ tolerance model	Fibre volume fraction		
		Ply thickness	Calculation, measurement	Part thickness
Applied vacuum level	Infusion trial			

To correctly design the digital framework, it is suggested that the relevant output parameters first be defined by considering the requirements for the finished product, followed by direct and input parameters and their relevant links. Working backwards in this way should avoid any relevant parameters from being overlooked, whilst ensuring the digital framework meets the process requirements.

6.4.1.2 Defining suitable procedures for measurement and control

After all parameters have been considered it is possible to define in further detail the necessary simulation, testing and measurement procedures. An example of this process is described for predicting the permeability of large preforms, as this is believed to be a non-standard process.

Currently, the reinforcement permeability tensors Kx, Ky and Kz are measured through a series of tightly controlled tests in which a sample of reinforcement is infused on a flat surface under a caul plate. The time for the resin to arrive at a set point is measured and can be used to back calculate permeability using Darcy's law if all other variables (porosity and resin viscosity) are known. Whilst these tests are sufficient for comparing different reinforcement types, they are not entirely representative of industrial manufacturing processes. Furthermore, accurate values of the reinforcement porosity must be known, and manufacturing variations can make it difficult to measure and predict these values.

To simplify this process, it is proposed that a series of more representative permeability trials be conducted for each discrete area of the part. These experiments capture the representative porosity within the permeability measurement, so it is possible to avoid measuring it, provided these tests are sufficiently representative of the manufacturing process. These representative infusion trials provide four key pieces of information that are required to simulate the infusion process and back-calculate the permeability tensors. These are: laminate thickness, fibre volume fraction and the periodical distance and time measurements corresponding to the resin flow front progression during the infusion. Resin density and reinforcement areal weight are also required to calculate the fibre volume fraction.

An identical digital reconstruction of the trial is then setup using flow simulation software. Optimisation software is then used to run several flow simulation iterations, back calculating the permeability tensors using only the set infusion time as a goal and the resin viscosity, part thickness and inlet/outlet pressures as inputs. Due to the proportional relationship between porosity, permeability and fill time within Darcy's law, any realistic value for porosity can be used within the simulations, provided the same value is used throughout. It is important to note that this method does not calculate the precise values of the permeability tensors, but rather a more accurate representation of their values within an industrial manufacturing process.

After all relevant parameters and their connections have been understood, it is possible to map the flow of information throughout the process to create a permeability module architecture. Combined with a resin viscosity module (to predict the realistic change in resin viscosity over time) one can create a flow simulation module architecture as presented in Figure 139.

6.4.1.3 Module Architecture

Having identified a suitable procedure for measuring and predicting the relevant process parameters, it is possible to construct a series of flow charts, or modules, that describe each section of the digital manufacturing process. This is one building block of the system-wise architecture. By mapping the process in this way, it is possible to clearly define the inputs and outputs of each module, thereby simplifying the system-wide architecture.

Figure 139 displays an example of a flow simulation module which could act as a software module in Figure 137. Figure 139 also includes the process of determining the permeability tensors that was described in the previous section. Other software modules include optimisation procedures and resin cure modelling, such as the multi-objective cure optimisation of resin cure profiles demonstrated by (G. Struzzero, 2016).

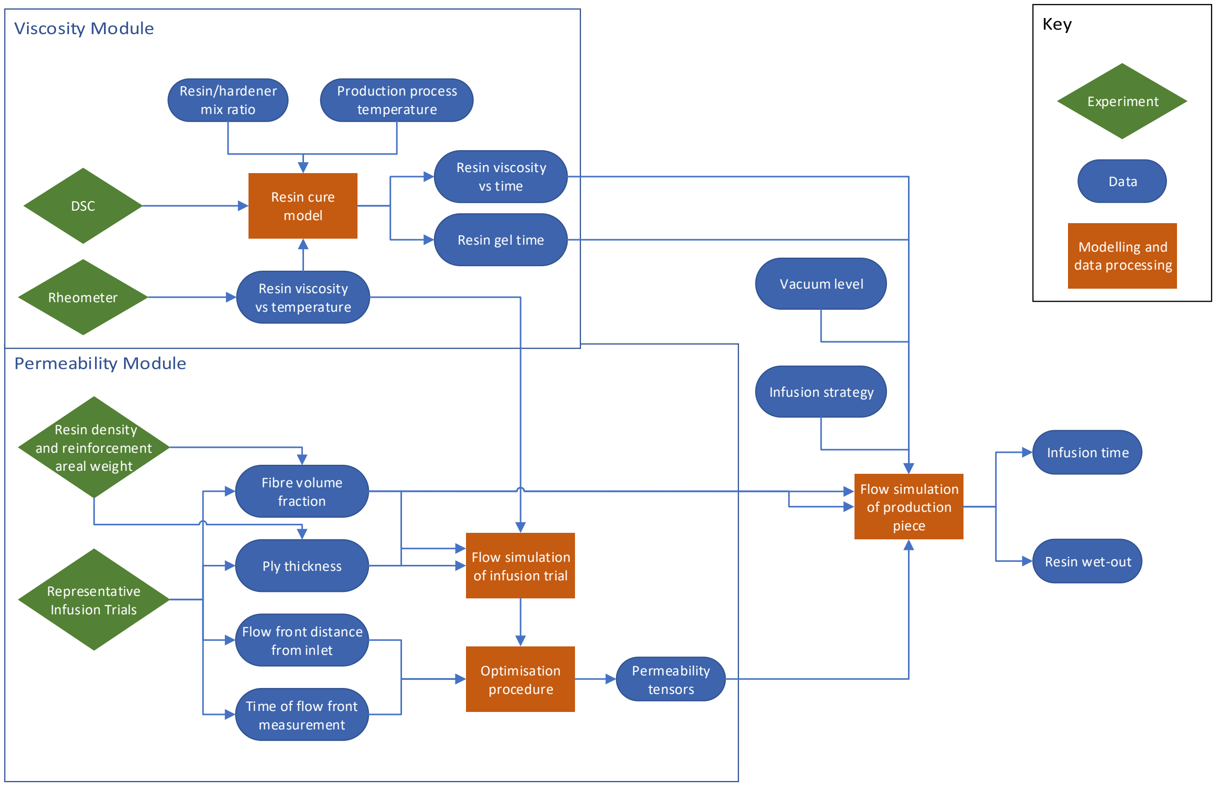


Figure 139: Flow simulation module architecture.

6.4.1.4 System-wide architecture

The system-wide architecture integrates all process modules together in a single flow chart, mapping the major flows of data throughout the production line. Figure 140 displays the system-wide architecture for an automated ship hull production concept. The architecture is split into three sections; software, sensors, and hardware, all controlled by a centralised control system. Each section is made up of standard modules, either equipment or digital tools. Each module is described by an architecture map as demonstrated previously for the infusion simulation in Figure 139.

Software modules are integrated together via a digital backbone; a separate piece of software that transfers relevant input and output data between the modules. The digital backbone allows standardised software modules to be used. For example, a customer is able to use their own FEA and infusion simulation tools by plugging them into the backbone. The digital backbone also transfers the relevant data from the software modules to the centralised control system.

Automation hardware forms the physical production line and is integrated via a centralised control system. Raw process data is extracted from the hardware using various sensors placed throughout the production line. Measured sensor data is used for system control and validation of the simulations.

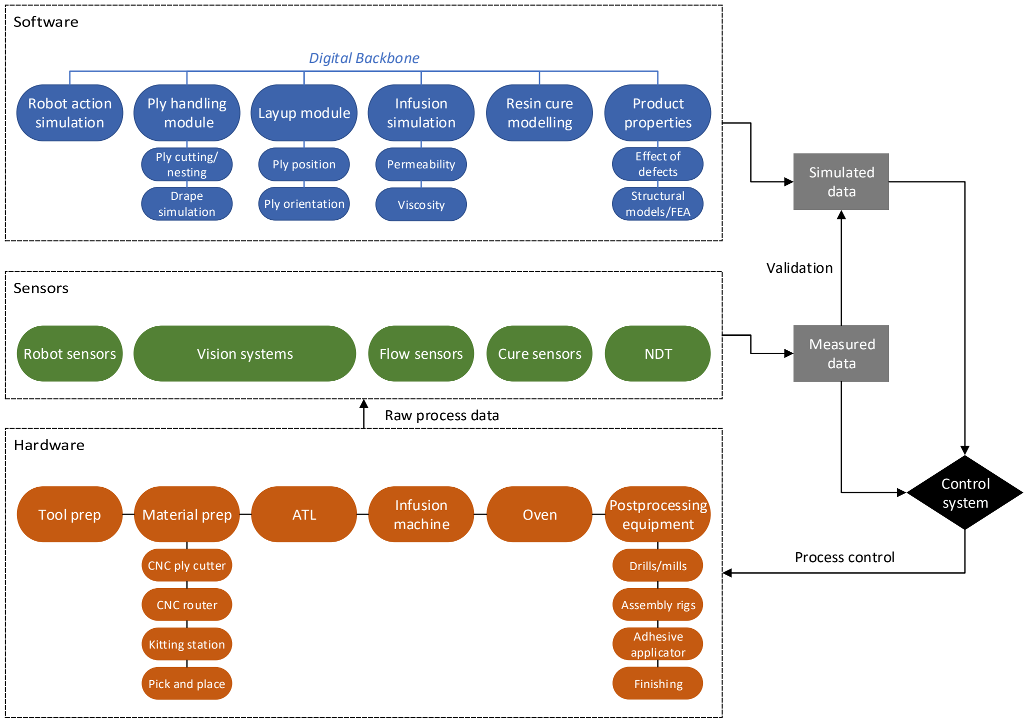


Figure 140: System-wide architecture for automated hull manufacturing concept.

Development and implementation of a digital backbone for automated composite manufacture is identified as a key area of further development. It should be noted that the individual modules featured in Figure 140 already exist. The novelty lies in bringing solutions together. As a final step, several production line concepts should be developed and compared against one another. Whilst the best solution for each process module has been selected in this proposed concept, they may not equate to the most effective production line when integrated together. Evaluating various production line concepts will highlight the best overall compromise. This final step is left as future work.

6.5 Conclusions and Future Work

This chapter presents an overview of the key automation challenges and potential automated manufacturing concepts for the selected case studies. The main purpose of this chapter is to outline the next steps of the hull shell manufacturing process development, which was presented in Chapter 5, which can be developed further in future research projects. The work primary focuses on the hull shell case study, building on the process developments presented in Chapters 3, 4, and 5, although a small section outlining a potential automated tidal turbine manufacturing concept is also presented. This section highlights the similarities between the two case studies regarding application of automated manufacturing solutions, and many of the solutions considered for the hull shell study are applied to the automated tidal turbine manufacturing concept. This work also identified some key technical challenges related to the tidal turbine case study (such as the effect of resin shrinkage on surface quality) which must be addressed in future work. The automated manufacturing concepts for the hull shell and tidal turbine blade feature commercially available solutions. The key area of further development was identified as being the integration of these individual automated hardware solutions via sensors and software to create fully automated manufacturing production lines. No fully automated production lines featuring resin infusion were identified in the market review, indicating that the concepts presented in the chapter could be further developed to generate novel manufacturing processes.

The work in this chapter primarily focuses on the hull shell case study. Several process requirements were outlined at the beginning of this chapter. Most of these have been addressed with the proposed concept:

- **The proposed manufacturing concept must be compatible with existing steel shipyard practices and contain the necessary equipment and infrastructure to handle and store large quantities of constituent composite materials.** The proposed concept features a large assembly process which is more compatible than a 75m long infusion. The smaller preform layup and infusion stages are conducted in an isolated environment away from the open shipyard. This enables a high level of quality control to be employed whilst avoiding large modifications to the shipyard.
- **An alternative layup solution is required to allow full access to the entire tool surface without using the tool surface as a means of moving around, as this could compromise the quality of the part.** The simplification of the layup process (smaller modular panels) enables full access to the tool surface.
- **An alternative solution is required to reduce the costs associated with tooling and improve the reliability of tool preparation procedures.** The modular panel approach significantly reduces the cost of tooling. A large assembly rig is required; however, this is much more affordable than a 75m long tool. The smaller tool combined with the automated application of release agent significantly improves the reliability of the tool preparation procedure.
- **An alternative solution is required to reduce the risks associated with infusing such a large structure.** The simplification of the infusion process towards smaller modular panels reduces the risk and financial consequence of infusion process issues and/or failure.
- **An alternative solution is required to reduce the risks imposed on the workforce and minimise changes to the current steel shipyard layout.** The isolation of the automated layup and infusion process steps separates the workforce from hazardous chemicals. The layup/infusion station is a minor modification to the existing shipyard, which will remain mostly unchanged.

- **Automated solutions are required to reduce manufacturing costs to enable a composite hull to compete with the steel alternative.** Further refinement of the manufacturing concept is required to generate representative process duration and cost estimates. A full cost-benefit analysis would also be required to account for the increased capital costs of automation equipment. This is beyond the scope of this initial automation study.
- **An automated closed control system is required to improve process robustness and quality control.** The digital framework presented in this chapter aims to improve product quality and process repeatability through implementation of integrated sensor-control systems and digital simulations. Setup of this concept in a physical production line is left for future work.

Overall, the automation concept presented in this work is a feasible solution based upon mostly existing technologies. However, this is only a concept, and there is much work still to be done to prove and implement this work. Further work is required to develop a robust assembly procedure for the modular hull shell. Adhesive bonding may be a suitable option as this method is implemented in the deck/bulkhead/shell assembly; however, this approach may lead to concerns over bond quality if conducted in a shipyard environment at such a large scale. An alternative approach has also been proposed in which semi-cured panels are co-infused together via local resin injections along the bond-lines. Further work is required to fully understand the strengths and weaknesses of this approach.

Following these refinements to the manufacturing process, a cost-benefit analysis must be conducted to demonstrate the potential cost reductions achievable with the automated manufacturing concept when considering the high capital investment associated with the physical and digital automation equipment. Following this, a full life-cycle assessment should be carried out to demonstrate the advantages of an autonomously manufactured composite ship hull compared to a conventional steel assembly. This supportive evidence will provide a company with sufficient confidence to implement the first stages of this concept into a physical production line. A small-scale prototype production line could be developed as a first step to refine the digital framework and the integration between hardware and software systems. The concept can then be applied to a full-scale production line within a shipyard. Whilst there is clearly a significant amount of work left to do, this chapter presents a critical first step towards the implementation of automated manufacturing solutions for this application. A similar approach could also be applied to the tidal turbine case study. However, further process refinements must be conducted to generate a feasible manufacturing process prior to implementation of automated technologies.

7 PROJECT CONCLUSIONS

The thesis has presented a comprehensive investigation that addresses the key challenges related to the manufacture of large marine composite structures. This final section outlines the major conclusions of the work and how these findings can be applied and further developed in industry.

7.1 Summary of Overall Findings

Composites provide many advantages over steels when applied to marine structures; however, the use of these materials creates new design and manufacturing challenges that must be addressed. As larger composite marine structures have gained greater commercial interest in recent years, these challenges have become focal points in academia and industry. The cost and financial risk associated with manufacturing and operating large composite marine structures such as tidal turbine blades and large hulls (50m+) was identified as the key primary cause for the limited use of composites in these applications. This thesis focuses on three key areas of research to address this issue: an investigation into faster and more cost-effective methods for predicting long-term laminate durability in marine environments, the development of manufacturing techniques for large marine structures using a composite ship hull as a case study, and the refinement of these techniques to create a commercially viable manufacturing solution. Additional challenges such as design certification and sustainability have also been highlighted.

An overall thesis research question was presented in Chapter 1:

Question: ***"Is it possible to produce large composite marine structures such as tidal turbine blades and large ship hulls that are both commercially and technically viable, using where appropriate, existing knowledge, materials, and processes?"***

Two project aims were defined to help answer this question. The work presented in this thesis mostly meets these aims, although further work is still required to develop commercial viability.

1. ***Reduce the cost and financial risk associated with predictions of long-term durability performance of composite laminates, relevant to a typical composites manufacturing company and the selected case studies.*** The methodology presented in Chapter 2 identifies ways in which the cost and duration of material conditioning activities can be reduced, especially those conducted for the purpose of initial material selection. Further development of constituent level modelling techniques is required to address the uncertainties related to long-term durability predictions.

2. ***Develop a manufacturing process for large composite marine structures that addresses the key manufacturing challenges and is relevant to the selected case studies and applicable within typical composites factory or shipyard.*** The manufacturing procedure presented in Chapter 5 demonstrates that a large composite hull shell can be produced in an industrial setting using existing knowledge, materials, and processes. The work addresses the key challenges related to vertical layup and infusion of large, thick composite structures. Further work is required to refine the commercial viability of this procedure using automated manufacturing technologies.

It can therefore be concluded that, with further research and development, it will be possible in the future to produce large composite marine structures such as tidal turbine blades and large ship hulls that are both commercially and technically viable, using where appropriate, existing knowledge, materials, and processes.

7.1.1 Durability and Testing of Composite Materials

Accurate predictions of long-term laminate durability in marine environments currently requires extensive physical testing of specimens which can be time consuming and costly. Knowledge of long-term material degradation can be critical for high-performance applications such as tidal turbine blades, where maintenance costs are high. An investigation was conducted to understand whether this process can be accelerated and simplified for the purpose of rapid material down-selection.

Interlaminar shear and flexural coupons were manufactured from a range of different marine composite laminates, conditioned in seawater until saturation, and then mechanically tested to failure. The data from these tests highlight the potential variation in mechanical properties and levels of degradation across the range of materials that are all marketed for marine applications, and thus the importance of material testing for commercial marine composite projects.

Current seawater conditioning techniques utilise conditioning temperatures of around 45°C to accelerate moisture uptake without compromising the state of the laminate by approaching the wet glass transition temperature of the resin, which for most marine applications is around 60-80°C. Raising the seawater temperature to 55°C was found to further accelerate the conditioning procedure for the selected laminates. However, this also resulted in, on average, slightly greater knockdowns in flexural and interlaminar strength, meaning accelerated conditioning procedures may be applied at the expense of more conservative structural designs.

It was found that higher levels of moisture uptake at saturation resulted in greater reductions in interlaminar strength across the range of different laminates and conditioning temperatures that were tested. This relationship suggests that laminates experiencing lower moisture uptake would therefore be preferable for the selected marine case studies. This should not be taken as a universal trend across all composite materials, and further work is suggested to investigate a wider range of composite laminates. However, if this trend is applicable to a wider range of marine composite laminates, it could be used together with numerical predictive methods to simplify and accelerate initial material down-selection. Utilising links between moisture uptake and mechanical degradation, together with Fick's Law (or alternatives) and Arrhenius relationships (to predict the effect of conditioning temperature on moisture diffusion rate and level of saturation) could allow engineers to rapidly predict the moisture degradation of a range of different laminates in a cost-effective manner using limited experimental data. Further refinements that consider resin chemical composition and model potential chemical reactions may improve the accuracy of these predictions. However, it is also important to consider the industrial applicability of this approach. The methodology proposed in this chapter can be applied in most composite design and manufacturing companies and only requires simple and widely available testing and conditioning equipment.

The complexity of the moisture degradation process and variability in laminate properties and manufacturing procedures mean that experimental testing cannot yet be avoided. Definition of standardised laminates and manufacturing procedures across the marine industry could reduce the duration and cost of experimental tests, and thus accelerate the adoption of composite materials in high-performance marine applications. However, such an approach could restrict innovation and adoption of more environmentally friendly alternative materials. A compromise between commercial and technical needs must therefore be found.

Novelty and value of research conducted: This work builds upon previous durability studies by investigating whether current sea water conditioning procedures can be further accelerated for a range of composite laminates typically used for commercial marine applications. The definition of standardised laminates for the marine industry and the use of general trends in experimental data are also suggested for reducing product development time and cost.

7.1.2 Manufacturing Large Composite Marine Structures

The lack of a robust and affordable manufacturing process for large composite marine structures was identified as a key limitation currently preventing the use of composite materials in larger vessels. To address this, the author conducted a manufacturing study focused on the composite hull case study selected in Chapter 1. In this study a manufacturing process for a fully composite 75m hull shell was developed and applied to successfully produce a full-scale, 2.3m wide demonstrator section. This manufacturing study was conducted within an industrial environment and driven by commercial needs and formed part of a wider European Research project known as RAMSSES. The author managed the hull shell manufacturing process development on behalf of Airborne UK, working in collaboration with project partners within the RAMSSES project to develop a commercial solution for a fully composite hull.

The limited duration and industrial setting of this project lead to the need for a rapid development approach to be utilised. This Chapter presents a rapid approach for developing manufacturing procedures for large, infused composite structures based upon representative experimental trials supported by expert industrial knowledge and prior manufacturing experience. This rapid approach was successfully applied to the case study, resulting in the production of a full-scale demonstrator within 18 months. The hull shell case study features novel design details such as 275mm thick monolithic and sandwich regions, 6m height, and a range of local shell-to-deck joint reinforcements. The initial hull shell design was modified by the author to facilitate the manufacture of this section with the selected features and manufacturing process. Project requirements relating to process duration and acceptable part quality were identified and used to evaluate the proposed manufacturing process.

Vacuum assisted resin infusion was selected as the most suitable manufacturing process as it currently provides the best compromise between product size, cost, and structural performance compared to other procedures. The use of a vacuum bag allowed for a more flexible and affordable manufacturing process; however, this method is sensitive to hydrostatic pressures when manufacturing large vertical sections. Therefore, infusing resin up to 6m in height was identified as the greatest process challenge for this application. A resin injection machine was used to counter the hydrostatic pressures, thus enabling the infusion of thick laminates up to 6m in height. In-plane and through-thickness resin flow within the preform was also investigated via a number of representative experiments. This enabled the development of a robust manufacturing process through suitable preform design and constituent material selection. The resulting infusion process produced a steady, uniform flow front progression up the preform that was insensitive to typical factory variations in temperature and humidity.

The full-scale demonstrator was successfully manufactured to meet most of the project requirements. Some defects and process issues were identified, which have been used to guide further process improvements. For example, a large dry region formed at the top of the part after the infusion process had completed due to vertical resin drainage because of a loss in vacuum pressure within the bag. A shorter resin cure time is thought to be an effective solution to minimise this draining effect. Two large (20mm) fibre-wrinkles were identified within the inner skin at the largest structural transitions. These defects were created during the layup procedure due to difficulties handling 9m long plies, thick laminate skins, limited debulking effectiveness and sharp transitions in sectional thickness. Design modifications that enable more gradual structural transitions combined with improved layup procedures are thought to be the most effective solutions to this problem.

The rapid development approach was shown to be effective in this project. The experimental findings of this novel manufacturing study highlight the importance of practical manufacturing trials. The author was able to gain significant insight into realistic layup tolerances, achievable part quality, and suitable methods for forming novel preform features. Furthermore, the author found that being directly involved with conducting experiments and manufacturing the demonstrator further accelerated the development activity, as it allowed the engineer to gain a more comprehensive understanding of the manufacturing challenges, and how these may impact the product design and/or quality.

The process issues previously discussed were not identified prior to the demonstrator manufacture, indicating that improvements to this rapid development approach could be made in the future. A full-scale reinforcement layup trial could have been conducted (simulating the structural transitions) prior to the demonstrator production. This investigation could have been conducted alongside the infusion development work and would have allowed the author to identify and quantify this issue, and thus generate a solution that could be applied to the demonstrator production. The issue of resin drainage was identified in the final infusion trial. Despite measures being taken to avoid this, robustness issues with the vacuum bag caused this process fault to occur in the demonstrator production. The author believes this to be an unavoidable risk linked to the use of disposable vacuum bags. Whilst this was an unfortunate event, the potential for vacuum bag leaks over a 75m hull shell are high and the resulting defects could compromise the structural integrity of the hull. The process is also quite manually intensive, resulting in significant process duration and cost. This has led to the consideration of design modifications and implementation of automated technologies, which are explored in further detail in Chapter 6.

Novelty and value of research conducted: A methodology is proposed to facilitate the rapid development of a resin infusion process for large composite marine structures. This was successfully applied to develop a one-shot infusion process for a 75m hull shell, and to manufacture a 6m high, full-scale demonstrator section of the hull shell that features monolithic and sandwich regions up to 280mm in thickness. Modifications to this process have been suggested for the production of a 75m hull shell in a shipyard environment.

7.1.3 Automated Manufacture of Large Composite Marine Structures

There are currently no examples of automated production lines being used to manufacture composite hulls or tidal turbine blades. Based upon the findings of the manufacturing study, a brief automation study was conducted to investigate potential automated manufacturing concepts for the selected case studies. The purpose of this study was to reduce manufacturing risk and cost by utilising currently available automation solutions where applicable.

A revised hull shell design is proposed that features modular panels instead of a single, continuous structure. This modular approach better accommodates existing automated manufacturing technologies and significantly reduces the risk associated with the resin infusion process. However, further work is required to develop a suitable and robust assembly procedure for these modular panels, as controlling the quality of adhesive bonds at this scale within a shipyard environment is challenging.

Existing automation technologies were found to be more compatible with the tidal turbine blade design, where no design modifications were required. However, it is important to note that this manufacturing concept is in the very early stages of development, and further process refinements are required. Nevertheless, it appears that the hardware and sensor technology required to automate this manufacturing process are currently commercially available.

Integration of existing automated manufacturing technologies was identified as a major gap in current manufacturing capabilities. Whilst robotics can currently be applied to individual process steps such as laying up materials on large tools, integration of these steps into a fully automated production line is currently lacking. The first stage of a methodology for designing and integrating an automated composites production line is presented; including both physical and digital infrastructure. Further research and development are required to apply this methodology to commercial production lines.

Novelty and value of research conducted: An automated manufacturing concept has been proposed for the two case studies using existing technologies, including a proposed methodology for integrating automated hardware and software packages. This work forms an initial basis upon which further process research and development activities can be conducted, with the ultimate aim of achieving fully automated production lines for the selected case studies.

7.2 Exploitation of Results and Future Work

Five key challenges were identified in chapter 1 that relate to the application of composite materials to large marine structures. Two of these challenges have been addressed in this work: Manufacturing capability and predictions of long-term material durability. Challenges related to cost and financial risk are also discussed in detail, with the work presented in this thesis forming a baseline upon which these challenges can be addressed in future work. This research can be applied alongside other developments in design certification and sustainability to lower the technical barriers of these applications and enable the wider application of composite materials to larger marine structures such as tidal turbine blades and ship hulls.

The research presented in chapter 2 highlights the key issues facing academia and industry relating to the prediction of long-term composite durability in a marine environment. Further developments in this area are required to achieve reductions in development time and cost for large composite marine structures. The proposed testing methodology could be an initial step towards this goal, however further testing of a wider range of composite laminates is required, alongside implementation of other non-Fickian diffusion models such as two-stage, sigmoidal and case II. Development and experimental validation of constituent level models would also help to reduce development time and cost. However, this methodology must be compatible with a typical composites company (i.e., no specialised/expensive lab equipment) if it is to be widely applied across the marine industry.

The wide range of available constituent materials, manufacturing processes and in-service conditions means that it is currently very difficult to accurately predict long-term material degradation. Whilst work is currently being done to investigate numerical predictive tools, experimental data is currently the primary method for determining long-term durability of composite laminates. To accelerate composite product development procedures across the marine industry, it may be suitable to define a set of "standard grade" composite materials that can be used by designers similar to how standard steel grades have been developed. Differences in manufacturing processes within the industry will no doubt result in variations among “standard grades” of composite laminates. However, definition of standard process parameters and constituent materials would be a positive step forward. This approach would allow academia and industry to focus research efforts on a few select materials, enabling a much more rapid understanding of how these materials behave and degrade over time, and thus increasing global confidence in large composite marine structures.

Selection of these standard constituent materials should be conducted based upon careful consideration of typical applications, material availability, range of existing data, and academic, industrial, and environmental needs. For example, three types of resins and fibres could be defined for use in large hulls to meet a range of commercial requirements such as cost and mechanical performance, resulting in 9 standard marine composite laminates that can be analysed and tested extensively across the globe. Restricting the choice of materials in this way may limit the implementation of more innovative materials, however the greater simplicity of durability predictions and product certification would likely out-weight this. Industry would also have to support this approach so concerns around innovation, competition, and IP would likely need to be addressed.

A rapid development approach is presented in this thesis that could be applied to other large-scale marine products. It is suggested that this approach be applied to tidal turbine blades to reduce the high development costs associated with this case study. Further refinements to this methodology should also be considered, such as the implementation of process simulations to further reduce the cost of experimental tests and enable a wider range of process parameters to be investigated in a much shorter duration. Expanding this methodology to other manufacturing processes relevant to marine structures such as RTM may also be considered.

The hull shell manufacturing process developed in this thesis addresses the key manufacturing challenges of this case study and can now be adopted and further developed by shipyards to produce large composite hulls for a variety of applications. Six key areas of further research are suggested for this manufacturing case study:

- The acceptance criteria should be revised based upon the suggestions made in this thesis. A combination of experimental tests and process modelling should be applied alongside hull structural calculations (and potentially finite element analysis) to investigate the effect of process defects on the mechanical performance of the structure, and hence identify a refined list of acceptable defects for this specific application.

- Further experimental trials and/or process simulations should be conducted to investigate the full range of shipyard environmental conditions. Test coupons could be manufactured at a variety of different environmental conditions and mechanically tested to quantify the effect of ambient conditions on structural performance.
- Apply the suggested design modifications to enable more gradual structural transitions and improve manufacturability of the hull shell, thereby reducing the risk of defects such as fibre wrinkles and bridging forming within the part.
- Apply the suggested process improvements to the hull shell manufacturing procedure and create a second full-scale demonstrator to ensure the part meets the project requirements and acceptance criteria.
- Scale up the manufacturing procedure and apply it within a shipyard to produce a 75m hull shell.
- Consider incorporating more environmentally sustainable composite materials into the hull shell design such as natural fibres and recyclable resin systems.

Alternatively, a shipyard may want to consider the automated manufacturing process as a way of producing composite hull shells in a more commercially viable manner. The automated manufacturing concepts for the hull shell and tidal turbine blade presented in this thesis act as a basis upon which further research can be conducted. The revised modular design of the hull shell is also thought to be more compatible with existing shipyard infrastructure and layout, whilst reducing overall production risk. Therefore, further development of this alternative design and manufacturing process may be of greater interest to shipyards for the continuous production of composite vessels. The following future developments are suggested to achieve automated production lines for the selected case studies:

- Develop and test small-scale demonstrator modules for individual automated manufacturing process steps (such as layup and resin infusion) using commercially available hardware and composite materials that are representative of the selected case studies. Integrate sensors into the hardware to measure and control the previously identified process parameters. Quantify achievable procedure tolerances and part quality levels and make modifications to the solutions as required to meet project requirements. Bespoke hardware solutions should be developed at this stage if products currently available on the market are unsuitable.
- Identify and/or develop suitable software tools for process modelling, control, and data management. Develop a digital twin manufacturing process simulation.
- Develop a digital framework that can be used to integrate individual hardware and software modules.

- Generate a detailed automated production line concept using the identified solutions. Use standard engineering tools such as value stream maps to demonstrate the advantages of the automated production line concept compared to conventional manual processes.
- Create a small-scale automated production line using the developed solutions. Integrate sensors to create a closed feedback loop. Validate the digital twin using this small-scale demonstrator and make refinements to both the hardware and software solutions as required. The small-scale demonstrator should be inspected and evaluated against the project requirements.
- Scale up the automated production line to a full-scale solution. The digital framework and sensor solutions developed for the small-scale production line should be directly applicable to this scaled-up version. Potentially expensive process and hardware redesigns should be conducted during the small-scale production line development phase. Therefore, this full-scale process development activity should focus only on scale-up modifications. A full-scale demonstrator should be manufactured using this production line. The full-scale demonstrator should be inspected and evaluated against the project requirements, and any final refinements to the process made before commercial application.

The following future developments are also suggested that relate specifically to the hull shell case study, which was the focus of this automation study:

- Further research is required to refine large-scale adhesive bonding procedures in a shipyard environment, including quantification of variations in process parameters and their effect on structural performance, and identification of suitable quality control procedures. Ensuring sufficient quality adhesive bonds at such large scales within a relatively uncontrolled shipyard environment is a difficult challenge and requires extensive research, both from a product design and manufacturing procedure perspective.
- Alternative hull shell assembly procedures should also be investigated such as the co-infusion of semi-cured modular panels via localised resin injection/infusion. The effect on part quality and structural performance should be evaluated alongside commercial factors such as duration and cost.

The research presented in this thesis represents the first steps towards addressing the major challenges currently preventing the use of composites in large marine structures. Further development of the material testing and manufacturing methodologies featured in this work will enable the composites industry to develop commercially viable solutions for large composite products that offer a wide range of benefits over conventional steel assemblies.

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APPENDIX

A.1: Hull Shell Manufacture: Ply Book

Table 50: Hull Shell Demonstrator: Ply Book

	PLY NO.	MATERIAL	VERTICAL POSITION ON TOOL (mm) (along tool surface, from bottom edge)		PLY LENGTH (mm)	PLY CONFIG.
			BOTTOM OF PLY	TOP OF PLY		
LOWER SKIN	1	SAER	100	9200	9100	X
	2	QI	100	9200	9100	1
	3	QI	100	932	832	2
	4	QI	100	4406	4306	3
	5	QI	100	9200	9100	4
	6	QI	100	1012	912	1
	7	QI	100	4486	4386	2
	8	QI	100	9200	9100	3
	9	QI	100	1092	992	4
	10	QI	100	4566	4466	1
	11	SAER	100	1172	1072	X
	12	QI	100	9200	9100	2
	13	QI	100	1252	1152	3
	14	QI	100	4646	4546	4
	15	QI	100	9200	9100	1
	16	QI	100	1332	1232	2
	17	QI	100	4726	4626	3
	18	QI	100	9200	9100	4
	19	QI	100	1412	1312	1
	20	QI	100	4806	4706	2
	21	SAER	100	9200	9100	X
	22	QI	100	9200	9100	3
	23	QI	100	1492	1392	4
	24	QI	100	4886	4786	1
	25	QI	100	9200	9100	2
	26	QI	100	1572	1472	3
	27	QI	100	4966	4866	4
	28	QI	100	9200	9100	1
	29	QI	100	1652	1552	2
	30	QI	100	5046	4946	3
	31	QI	100	9200	9100	4
	32	QI	100	1732	1632	1
	33	SAER	100	1812	1712	X
	34	QI	100	5126	5026	2

	35	QI	100	9200	9100	3
	36	QI	100	1892	1792	4
	37	QI	100	5206	5106	1
	38	QI	100	9200	9100	2
	39	QI	100	1972	1872	3
	40	QI	100	5286	5186	4
	41	QI	100	9200	9100	1
	42	QI	100	2052	1952	2
	43	QI	100	2132	2032	3
	44	QI	100	2212	2112	4
	45	SAER	100	9200	9100	X
CORE	C1	CORE SHEETS AS PER DRAWING				
	46	SAER	500	9200	8700	X
	C2	CORE SHEETS AS PER DRAWING				
	47	SAER	500	9200	8700	X
	C3	CORE SHEETS AS PER DRAWING				
	48	SAER	500	9200	8700	X
	C4	CORE SHEETS AS PER DRAWING				
	49	SAER	500	9200	8700	X
MONO	50	QI	100	500	400	1
	51	QI	100	501	401	2
	52	QI	100	503	403	1
	53	QI	100	504	404	2
	54	QI	100	506	406	1
	55	QI	100	507	407	2
	56	QI	100	509	409	1
	57	QI	100	510	410	2
	58	QI	100	512	412	1
	59	QI	100	513	413	2
	60	SAER	100	515	415	X
	61	QI	100	516	416	1
	62	QI	100	518	418	2
	63	QI	100	519	419	1
	64	QI	100	520	420	2
	65	QI	100	522	422	1
	66	QI	100	523	423	2
	67	QI	100	525	425	1
	68	QI	100	526	426	2
	69	QI	100	528	428	1
	70	QI	100	529	429	2
	71	SAER	100	531	431	X
	72	QI	100	532	432	1
	73	QI	100	534	434	2

	74	QI	100	535	435	1
	75	QI	100	536	436	2
	76	QI	100	538	438	1
	77	QI	100	539	439	2
	78	QI	100	541	441	1
	79	QI	100	542	442	2
	80	QI	100	544	444	1
	81	QI	100	545	445	2
	82	SAER	100	547	447	X
	83	QI	100	548	448	1
	84	QI	100	550	450	2
	85	QI	100	551	451	1
	86	QI	100	553	453	2
	87	QI	100	554	454	1
	88	QI	100	555	455	2
	89	QI	100	557	457	1
	90	QI	100	558	458	2
	91	QI	100	560	460	1
	92	QI	100	561	461	2
	93	SAER	100	563	463	X
	94	QI	100	564	464	1
	95	QI	100	566	466	2
	96	QI	100	567	467	1
	97	QI	100	569	469	2
	98	QI	100	570	470	1
	99	QI	100	571	471	2
	100	QI	100	573	473	1
	101	QI	100	574	474	2
	102	QI	100	576	476	1
	103	QI	100	577	477	2
	104	SAER	100	579	479	X
	105	QI	100	580	480	1
	106	QI	100	582	482	2
	107	QI	100	583	483	1
	108	QI	100	585	485	2
	109	QI	100	586	486	1
	110	QI	100	588	488	2
	111	QI	100	589	489	1
	112	QI	100	590	490	2
	113	QI	100	592	492	1
	114	QI	100	593	493	2
	115	SAER	100	595	495	X
	116	QI	100	596	496	1

	117	QI	100	598	498	2
	118	QI	100	599	499	1
	119	QI	100	601	501	2
	120	QI	100	602	502	1
	121	QI	100	604	504	2
	122	QI	100	605	505	1
	123	QI	100	607	507	2
	124	QI	100	608	508	1
	125	QI	100	609	509	2
	126	SAER	100	611	511	X
	127	QI	100	612	512	1
	128	QI	100	614	514	2
	129	QI	100	615	515	1
	130	QI	100	617	517	2
	131	QI	100	618	518	1
	132	QI	100	620	520	2
	133	QI	100	621	521	1
	134	QI	100	623	523	2
	135	QI	100	624	524	1
	136	QI	100	625	525	2
	137	SAER	100	627	527	X
	138	QI	100	628	528	1
	139	QI	100	630	530	2
	140	QI	100	631	531	1
	141	QI	100	633	533	2
	142	QI	100	634	534	1
	143	QI	100	636	536	2
	144	QI	100	637	537	1
	145	QI	100	639	539	2
	146	QI	100	640	540	1
	147	QI	100	642	542	2
	148	SAER	100	643	543	X
	149	QI	100	644	544	1
	150	QI	100	646	546	2
	151	QI	100	647	547	1
	152	QI	100	649	549	2
	153	QI	100	650	550	1
	154	QI	100	652	552	2
	155	QI	100	653	553	1
	156	QI	100	655	555	2
	157	QI	100	656	556	1
	158	QI	100	658	558	2
	159	SAER	100	659	559	X

	160	QI	100	660	560	1
	161	QI	100	662	562	2
	162	QI	100	663	563	1
	163	QI	100	665	565	2
	164	QI	100	666	566	1
	165	QI	100	668	568	2
	166	QI	100	669	569	1
	167	QI	100	671	571	2
	168	QI	100	672	572	1
	169	QI	100	674	574	2
	170	SAER	100	675	575	X
	171	QI	100	677	577	1
	172	QI	100	678	578	2
	173	QI	100	679	579	1
	174	QI	100	681	581	2
	175	QI	100	682	582	1
	176	QI	100	684	584	2
	177	QI	100	685	585	1
	178	QI	100	687	587	2
	179	QI	100	688	588	1
	180	QI	100	690	590	2
	181	SAER	100	691	591	X
	182	QI	100	693	593	1
	183	QI	100	694	594	2
	184	QI	100	695	595	1
	185	QI	100	697	597	2
	186	QI	100	698	598	1
	187	QI	100	700	600	2
	188	QI	100	701	601	1
	189	QI	100	703	603	2
	190	QI	100	704	604	1
	191	QI	100	706	606	2
	192	SAER	100	707	607	X
	193	QI	100	709	609	1
	194	QI	100	710	610	2
	195	QI	100	712	612	1
	196	QI	100	713	613	2
	197	QI	100	714	614	1
	198	QI	100	716	616	2
	199	QI	100	717	617	1
	200	QI	100	719	619	2
	201	QI	100	720	620	1
	202	QI	100	722	622	2

	203	SAER	100	723	623	X
	204	QI	100	725	625	1
	205	QI	100	726	626	2
	206	QI	100	728	628	1
	207	QI	100	729	629	2
	208	QI	100	731	631	1
	209	QI	100	732	632	2
	210	QI	100	733	633	1
	211	QI	100	735	635	2
	212	QI	100	736	636	1
	213	QI	100	738	638	2
	214	SAER	100	739	639	X
	215	QI	100	741	641	1
	216	QI	100	742	642	2
	217	QI	100	744	644	1
	218	QI	100	745	645	2
	219	QI	100	747	647	1
	220	QI	100	748	648	2
	221	QI	100	749	649	1
	222	QI	100	751	651	2
	223	QI	100	752	652	1
	224	QI	100	754	654	2
	225	SAER	100	755	655	X
	226	QI	100	757	657	1
	227	QI	100	758	658	2
	228	QI	100	760	660	1
	229	QI	100	761	661	2
	230	QI	100	763	663	1
	231	QI	100	764	664	2
	232	QI	100	766	666	1
	233	QI	100	767	667	2
	234	QI	100	768	668	1
	235	QI	100	770	670	2
	236	SAER	100	771	671	X
	237	QI	100	773	673	1
	238	QI	100	774	674	2
	239	QI	100	776	676	1
	240	QI	100	777	677	2
	241	QI	100	779	679	1
	242	QI	100	780	680	2
	243	QI	100	782	682	1
	244	QI	100	783	683	2
	245	QI	100	784	684	1

	246	QI	100	786	686	2
	247	SAER	100	787	687	X
	248	QI	100	789	689	1
	249	QI	100	790	690	2
	250	QI	100	792	692	1
	251	QI	100	793	693	2
	252	QI	100	795	695	1
	253	QI	100	796	696	2
	254	QI	100	798	698	1
	255	QI	100	799	699	2
	256	QI	100	801	701	1
	257	QI	100	802	702	2
	258	SAER	100	803	703	X
	259	QI	100	805	705	1
	260	QI	100	806	706	2
	261	QI	100	808	708	1
	262	QI	100	809	709	2
	263	QI	100	811	711	1
	264	QI	100	812	712	2
	265	QI	100	814	714	1
	266	QI	100	815	715	2
	267	QI	100	817	717	1
	268	QI	100	818	718	2
	269	SAER	100	820	720	X
	270	QI	100	821	721	1
	271	QI	100	822	722	2
	272	QI	100	824	724	1
	273	QI	100	825	725	2
	274	QI	100	827	727	1
	275	QI	100	828	728	2
	276	QI	100	830	730	1
	277	QI	100	831	731	2
	278	QI	100	833	733	1
	279	QI	100	834	734	2
	280	SAER	100	836	736	X
	281	QI	100	837	737	1
	282	QI	100	838	738	2
	283	QI	100	840	740	1
	284	QI	100	841	741	2
	285	QI	100	843	743	1
	286	QI	100	844	744	2
	287	QI	100	846	746	1
	288	QI	100	847	747	2

	289	QI	100	849	749	1
	290	QI	100	850	750	2
	291	QI	100	852	752	1
UPPER SKIN	292	SAER	100	9200	9100	X
	293	QI	100	2312	2212	4
	294	QI	100	2232	2132	3
	295	QI	100	2152	2052	2
	296	QI	100	9200	9100	1
	297	QI	100	5286	5186	4
	298	QI	100	2072	1972	3
	299	QI	100	9200	9100	2
	300	QI	100	5206	5106	1
	301	QI	100	1992	1892	4
	302	QI	100	9200	9100	3
	303	QI	100	5126	5026	2
	304	SAER	100	1912	1812	X
	305	QI	100	1832	1732	1
	306	QI	100	9200	9100	4
	307	QI	100	5046	4946	3
	308	QI	100	1752	1652	2
	309	QI	100	9200	9100	1
	310	QI	100	4966	4866	4
	311	QI	100	1672	1572	3
	312	QI	100	9200	9100	2
	313	QI	100	4886	4786	1
	314	QI	100	1592	1492	4
	315	QI	100	9200	9100	3
	316	SAER	100	9200	9100	X
	317	QI	100	4806	4706	2
	318	QI	100	1512	1412	1
	319	QI	100	9200	9100	4
	320	QI	100	4726	4626	3
	321	QI	100	1432	1332	2
	322	QI	100	9200	9100	1
	323	QI	100	4646	4546	4
	324	QI	100	1352	1252	3
	325	QI	100	9200	9100	2
	326	SAER	100	1272	1172	X
	327	QI	100	4566	4466	1
	328	QI	100	1192	1092	4
	329	QI	100	9200	9100	3
	330	QI	100	4486	4386	2
	331	QI	100	1112	1012	1

	332	QI	100	9200	9100	4
	333	QI	100	4406	4306	3
	334	QI	100	1032	932	2
	335	QI	100	9200	9100	1
	336	SAER	100	9200	9100	X

JOINT 1 MONOLITHIC INSERT

	PLY NO.	MATERIAL	Position from start of ply 1		PLY LENGTH (mm)	PLY CONFIG.
			START OF PLY	END OF PLY		
JOINT 1 INSERT	1	QI	3826	4326	500	1
	2	QI	3826	4326	500	2
	3	QI	3826	4326	500	1
	4	QI	3826	4326	500	2
	5	QI	3826	4326	500	1
	6	QI	3826	4326	500	2
	7	QI	3826	4326	500	1
	8	QI	3826	4326	500	2
	9	QI	3826	4326	500	1
	10	QI	3826	4326	500	2
	11	SAER	3826	4326	500	X
	12	QI	3826	4326	500	1
	13	QI	3826	4326	500	2
	14	QI	3826	4326	500	1
	15	QI	3826	4326	500	2
	16	QI	3826	4326	500	1
	17	QI	3826	4326	500	2
	18	QI	3826	4326	500	1
	19	QI	3826	4326	500	2
	20	QI	3826	4326	500	1
	21	QI	3826	4326	500	2
	22	SAER	3826	4326	500	X
	23	QI	3826	4326	500	1
	24	QI	3826	4326	500	2
	25	QI	3826	4326	500	1
	26	QI	3826	4326	500	2
	27	QI	3826	4326	500	1
	28	QI	3826	4326	500	2
	29	QI	3826	4326	500	1
	30	QI	3826	4326	500	2
	31	QI	3826	4326	500	1
	32	QI	3826	4326	500	2
	33	SAER	3826	4326	500	X
	34	QI	3826	4326	500	1

	35	QI	3826	4326	500	2
	36	QI	3826	4326	500	1
	37	QI	3826	4326	500	2
	38	QI	3826	4326	500	1
	39	QI	3826	4326	500	2
	40	QI	3826	4326	500	1
	41	QI	3826	4326	500	2
	42	QI	3826	4326	500	1
	43	QI	3826	4326	500	2
	44	SAER	3826	4326	500	X
	45	QI	3826	4326	500	1
	46	QI	3826	4326	500	2
	47	QI	3826	4326	500	1
	48	QI	3826	4326	500	2
	49	QI	3826	4326	500	1
	50	QI	3826	4326	500	2
	51	QI	3826	4326	500	1
	52	QI	3826	4326	500	2
	53	QI	3826	4326	500	1
	54	QI	3826	4326	500	2
	55	SAER	3826	4326	500	X
	56	QI	3826	4326	500	1
	57	QI	3826	4326	500	2
	58	QI	3826	4326	500	1
	59	QI	3826	4326	500	2
	60	QI	3826	4326	500	1
	61	QI	3826	4326	500	2
	62	QI	3826	4326	500	1
	63	QI	3826	4326	500	2
	64	QI	3826	4326	500	1
	65	QI	3826	4326	500	2
	66	SAER	3826	4326	500	X
	67	QI	3826	4326	500	1
	68	QI	3826	4326	500	2
	69	QI	3826	4326	500	1
	70	QI	3826	4326	500	2
	71	QI	3826	4326	500	1
	72	QI	3826	4326	500	2
	73	QI	3826	4326	500	1
	74	QI	3826	4326	500	2
	75	QI	3826	4326	500	1
	76	QI	3826	4326	500	2
	77	SAER	3826	4326	500	X

	78	QI	3826	4326	500	1
	79	QI	3826	4326	500	2
	80	QI	3826	4326	500	1
	81	QI	3826	4326	500	2
	82	QI	3826	4326	500	1
	83	QI	3826	4326	500	2
	84	QI	3826	4326	500	1
	85	QI	3826	4326	500	2
	86	QI	3826	4326	500	1
	87	QI	3826	4326	500	2
	88	SAER	3826	4326	500	X
	89	QI	3826	4326	500	1
	90	QI	3826	4326	500	2
	91	QI	3826	4326	500	1
	92	QI	3826	4326	500	2
	93	QI	3826	4326	500	1
	94	QI	3826	4326	500	2
	95	QI	3826	4326	500	1
	96	QI	3826	4326	500	2
	97	QI	3826	4326	500	1
	98	QI	3826	4326	500	2
	99	SAER	3826	4326	500	X
	100	QI	3826	4326	500	1
	101	QI	3826	4326	500	2
	102	QI	3826	4326	500	1
	103	QI	3826	4326	500	2
	104	QI	3826	4326	500	1
	105	QI	3826	4326	500	2
	106	QI	3826	4326	500	1
	107	QI	3826	4326	500	2
	108	QI	3826	4326	500	1
	109	QI	3826	4326	500	2
	110	SAER	3826	4326	500	X
	111	QI	3826	4326	500	1
	112	QI	3826	4326	500	2
	113	QI	3826	4326	500	1
	114	QI	3826	4326	500	2
	115	QI	3826	4326	500	1
	116	QI	3826	4326	500	2
	117	QI	3826	4326	500	1
	118	QI	3826	4326	500	2
	119	QI	3826	4326	500	1
	120	QI	3826	4326	500	2

	121	SAER	3826	4326	500	X
	122	QI	3826	4146	320	1
	123	QI	3826	4145	319	2
	124	QI	3826	4144	318	1
	125	QI	3826	4143	317	2
	126	QI	3826	4142	316	1
	127	QI	3826	4140	314	2
	128	QI	3826	4139	313	1
	129	QI	3826	4138	312	2
	130	QI	3826	4137	311	1
	131	QI	3826	4136	310	2
	132	SAER	3826	4135	309	X
	133	QI	3826	4134	308	1
	134	QI	3826	4133	307	2
	135	QI	3826	4131	305	1
	136	QI	3826	4130	304	2
	137	QI	3826	4129	303	1
	138	QI	3826	4128	302	2
	139	QI	3826	4127	301	1
	140	QI	3826	4126	300	2
	141	QI	3826	4125	299	1
	142	QI	3826	4124	298	2
	143	SAER	3826	4122	296	X
	144	QI	3826	4121	295	1
	145	QI	3826	4120	294	2
	146	QI	3826	4119	293	1
	147	QI	3826	4118	292	2
	148	QI	3826	4117	291	1
	149	QI	3826	4116	290	2
	150	QI	3826	4115	289	1
	151	QI	3826	4113	287	2
	152	QI	3826	4112	286	1
	153	QI	3826	4111	285	2
	154	SAER	3826	4110	284	X
	155	QI	3826	4109	283	1
	156	QI	3826	4108	282	2
	157	QI	3826	4107	281	1
	158	QI	3826	4106	280	2
	159	QI	3826	4104	278	1
	160	QI	3826	4103	277	2
	161	QI	3826	4102	276	1
	162	QI	3826	4101	275	2
	163	QI	3826	4100	274	1

	164	QI	3826	4099	273	2
	165	SAER	3826	4098	272	X
	166	QI	3826	4097	271	1
	167	QI	3826	4095	269	2
	168	QI	3826	4094	268	1
	169	QI	3826	4093	267	2
	170	QI	3826	4092	266	1
	171	QI	3826	4091	265	2
	172	QI	3826	4090	264	1
	173	QI	3826	4089	263	2
	174	QI	3826	4088	262	1
	175	QI	3826	4086	260	2
	176	SAER	3826	4085	259	X
	177	QI	3826	4084	258	1
	178	QI	3826	4083	257	2
	179	QI	3826	4082	256	1
	180	QI	3826	4081	255	2
	181	QI	3826	4080	254	1
	182	QI	3826	4079	253	2
	183	QI	3826	4077	251	1
	184	QI	3826	4076	250	2
	185	QI	3826	4075	249	1
	186	QI	3826	4074	248	2
	187	SAER	3826	4073	247	X
	188	QI	3826	4072	246	1
	189	QI	3826	4071	245	2
	190	QI	3826	4070	244	1
	191	QI	3826	4068	242	2
	192	QI	3826	4067	241	1
	193	QI	3826	4066	240	2
	194	QI	3826	4065	239	1
	195	QI	3826	4064	238	2
	196	QI	3826	4063	237	1
	197	QI	3826	4062	236	2
	198	SAER	3826	4061	235	X
	199	QI	3826	4059	233	1
	200	QI	3826	4058	232	2
	201	QI	3826	4057	231	1
	202	QI	3826	4056	230	2
	203	QI	3826	4055	229	1
	204	QI	3826	4054	228	2
	205	QI	3826	4053	227	1
	206	QI	3826	4052	226	2

	207	QI	3826	4050	224	1
	208	QI	3826	4049	223	2
	209	SAER	3826	4048	222	X
	210	QI	3826	4047	221	1
	211	QI	3826	4046	220	2
	212	QI	3826	4045	219	1
	213	QI	3826	4044	218	2
	214	QI	3826	4043	217	1
	215	QI	3826	4041	215	2
	216	QI	3826	4040	214	1
	217	QI	3826	4039	213	2
	218	QI	3826	4038	212	1
	219	QI	3826	4037	211	2
	220	SAER	3826	4036	210	X
	221	QI	3826	4035	209	1
	222	QI	3826	4034	208	2
	223	QI	3826	4032	206	1
	224	QI	3826	4031	205	2
	225	QI	3826	4030	204	1
	226	QI	3826	4029	203	2
	227	QI	3826	4028	202	1
	228	QI	3826	4027	201	2
	229	QI	3826	4026	200	1
	230	QI	3826	4025	199	2
	231	SAER	3826	4023	197	X
	232	QI	3826	4022	196	1
	233	QI	3826	4021	195	2
	234	QI	3826	4020	194	1
	235	QI	3826	4019	193	2
	236	QI	3826	4018	192	1
	237	QI	3826	4017	191	2
	238	QI	3826	4016	190	1
	239	QI	3826	4014	188	2
	240	QI	3826	4013	187	1
	241	QI	3826	4012	186	2

JOINT 2 SHEAR TIES AND MONOLITHIC						
	PLY NO.	MATERIAL	Position from start of ply 1		PLY LENGTH (mm)	PLY CONFIG.
			START OF PLY	END OF PLY		
Shear Tie 1A	1	QI	Drape around SP2 core top edge		463	1
	2	QI	Drape around SP2 core top edge		463	2
	3	QI	Drape around SP2 core top edge		463	1
	4	QI	Drape around SP2 core top edge		463	2

	5	QI	Drape around SP2 core top edge	463	1
	6	QI	Drape around SP2 core top edge	463	2
Shear Tie 1B & 2B	7	SAER	Wrap around joint 2 core insert	421	X
	8	QI	Wrap around joint 2 core insert	421	1
	9	QI	Wrap around joint 2 core insert	421	2
	10	QI	Wrap around joint 2 core insert	421	1
	11	QI	Wrap around joint 2 core insert	421	2
	12	QI	Wrap around joint 2 core insert	421	1
	13	QI	Wrap around joint 2 core insert	421	2
	14	SAER	Insert in middle of lower shear tie	143	X
	15	SAER	Insert in middle of upper shear tie	85	X
Shear Tie 2A	16	QI	Drape around SP3 core bottom edge	405	1
	17	QI	Drape around SP3 core bottom edge	405	2
	18	QI	Drape around SP3 core bottom edge	405	1
	19	QI	Drape around SP3 core bottom edge	405	2
	20	QI	Drape around SP3 core bottom edge	405	1
	21	QI	Drape around SP3 core bottom edge	405	2

	PLY NO.	MATERIAL	Position from start of ply 1		PLY LENGTH (mm)	PLY CONFIG.
			START OF PLY	END OF PLY		
Joint 2 Mono	1	QI	0	80	80	2
	2	QI	1.41	79.19	78	1
	3	QI	2.81	78.38	76	2
	4	QI	4.22	77.56	73	1
	5	QI	5.63	76.75	71	2
	6	QI	7.03	75.94	69	1
	7	QI	8.44	75.13	67	2
	8	QI	9.84	74.32	64	1
	9	QI	11.25	73.50	62	2
	10	QI	12.66	72.69	60	1
	11	SAER	14.06	71.88	58	X
	12	QI	15.47	71.07	56	2
	13	QI	16.88	70.26	53	1
	14	QI	18.28	69.44	51	2
	15	QI	19.69	68.63	49	1
	16	QI	21.10	67.82	47	2
	17	QI	22.50	67.01	45	1
	18	QI	23.91	66.20	42	2
	19	QI	25.32	65.38	40	1
	20	QI	26.72	64.57	38	2
	21	QI	28.13	63.76	36	1

	22	SAER	29.53	62.95	33	X
	23	QI	30.94	62.14	31	2
	24	QI	32.35	61.32	29	1
	25	QI	33.75	60.51	27	2
	26	QI	35.16	59.70	25	1
	27	QI	36.57	58.89	22	2
	28	QI	37.97	58.08	20	1
	29	QI	39.38	57.26	18	2
	30	QI	40.79	56.45	16	1
	31	QI	42.19	55.64	13	2
	32	QI	43.60	54.83	11	1
Over-laminate	1	QI	6629	7129	500	2
	2	QI	6649	7149	500	1
	3	QI	6669	7169	500	2
	4	QI	6689	7189	500	1

JOINT 3 MONOLITHIC (TOP OF SP3)						
	PLY NO.	MATERIAL	Position from start of ply 1		PLY LENGTH (mm)	PLY CONFIG.
			START OF PLY	END OF PLY		
Joint 3 Mono	1	QI	0	410	410	2
	2	QI	0.83	410	409	1
	3	QI	1.67	410	408	2
	4	QI	2.50	410	408	1
	5	QI	3.33	410	407	2
	6	QI	4.17	410	406	1
	7	QI	5.00	410	405	2
	8	QI	5.83	410	404	1
	9	QI	6.67	410	403	2
	10	QI	7.50	410	403	1
	11	QI	8.33	410	402	2
	12	SAER	9.17	410	401	X
	13	QI	10.00	410	400	1
	14	QI	10.83	410	399	2
	15	QI	11.67	410	398	1
	16	QI	12.50	410	398	2
	17	QI	13.33	410	397	1
	18	QI	14.17	410	396	2
	19	QI	15.00	410	395	1
	20	QI	15.83	410	394	2
	21	QI	16.67	410	393	1
	22	QI	17.50	410	393	2

	23	QI	18.33	410	392	1
	24	SAER	19.17	410	391	X
	25	QI	20.00	403.75	384	2
	26	QI	20.83	397.50	377	1
	27	QI	21.67	391.25	370	2
	28	QI	22.50	385.00	363	1
	29	QI	23.33	378.75	355	2
	30	QI	24.17	372.50	348	1
	31	QI	25.00	366.25	341	2
	32	QI	25.83	360.00	334	1
	33	QI	26.67	353.75	327	2
	34	QI	27.50	347.50	320	1
	35	QI	28.33	341.25	313	2
	36	SAER	29.17	335.00	306	X
	37	QI	30.00	328.75	299	1
	38	QI	30.83	322.50	292	2
	39	QI	31.67	316.25	285	1
	40	QI	32.50	310.00	278	2
	41	QI	33.33	303.75	270	1
	42	QI	34.17	297.50	263	2
	43	QI	35.00	291.25	256	1
	44	QI	35.83	285.00	249	2
	45	QI	36.67	278.75	242	1
	46	QI	37.50	272.50	235	2
	47	QI	38.33	266.25	228	1
	48	SAER	39.17	260.00	221	X
	49	QI	40.00	253.75	214	2
	50	QI	40.83	247.50	207	1
	51	QI	41.67	241.25	200	2
	52	QI	42.50	235.00	193	1
	53	QI	43.33	228.75	185	2
	54	QI	44.17	222.50	178	1
	55	QI	45.00	216.25	171	2
	56	QI	45.83	210.00	164	1
	57	QI	46.67	203.75	157	2
	58	QI	47.50	197.50	150	1
	59	QI	48.33	191.25	143	2
	60	SAER	49.17	185.00	136	X
	61	QI	50.00	178.75	129	1
	62	QI	50.83	172.50	122	2
	63	QI	51.67	166.25	115	1
	64	QI	52.50	160.00	108	2
	65	QI	53.33	153.75	100	1

	66	QI	54.17	147.50	93	2
	67	QI	55.00	141.25	86	1
	68	QI	55.83	135.00	79	2
	69	QI	56.67	128.75	72	1
	70	QI	57.50	122.50	65	2
	71	QI	58.33	116.25	58	1
	72	QI	59.17	110.00	51	2

A.2: Hull Shell Manufacture: Tool Preparation Investigation

A study has been conducted to select a suitable tool preparation method for use in the demonstrator production. Several tool surface preparation techniques were tested.

Introduction

The purpose of this study is to identify the most suitable release agent/tool preparation technique for use in the RAMSSES demonstrator production. Tool preparation is required to ensure the part can release well from the tool after cure. A number of different options were investigated:

1. Crinkle bag directly onto tool surface
2. Bleedex covered with vacuum bag
3. Surface tissue covered with vacuum bag
4. PVA release agent
5. Honey wax with PVA on top
6. Honey wax with R500 (brush on release agent) on top
7. R500 on tool surface

Method

Each option was tested with an infusion trial on the final demonstrator tool. The relevant tool preparation was applied to a small area of the tool (near the base where it is relatively flat and easily accessible). A single ply of saerflow was then vacuum bagged over the prepared area and infused with Albidur 3.2 resin (1% weloxan, 0.5% pergaquick). The following evaluation criteria were used to determine the most suitable option:

- Ease of release from tool
- Laminate surface quality/roughness
- Ease of application
- Suitability for double curvatures and more complex shapes
- Cost
- Ability to support the weight and hold material on vertical section of tool

Results

This section discusses the strengths and weaknesses of each tool preparation option. A summary of these results is presented in Table 51.

Options 1, 2, 3, 5, 6 and 7 offered good release from the tool. Option 4 was more difficult to release from the tool and required more of a peeling action, which would not be possible for the demonstrator (due to its size and laminate thickness).

Options 4, 5, 6 and 7 provided the best laminate surface quality, with a smooth and even surface. The crinkle bag pattern was imprinted into the laminate on option 1, providing a some-what rough but even pattern. Options 2 and 3 resulted in a bumpier and uneven surface where the bleedex and surface tissue had been imprinted into the laminate surface respectively. Option 2 with bleedex was noticeably worse.

Options 4 (PVA) and 7 (R500) were the easiest to apply to the tool (via brush or spray). Options 1, 2 and 3 required careful layup of more expensive bagging materials onto the tool. Options 5 and 6 both use honey wax, requiring 5 coats, each polished by hand and left to set. This is a very labour-intensive task for such a large tool.

Options 4 through 7 can be applied to almost any shaped surface. Options 1 through 3 are difficult to apply to double curvatures, where draping of the bagging materials will result in folds and creases. There are also additional concerns with robustness when using bagging materials (leaks, imperfect seals).

The PVA is the cheapest option. R500 is slightly more expensive. Bagging materials and consumables required for options 1 through 3 are quite expensive.

The ability to support vertical weight of material has yet to be investigated. This will likely be done at a later stage as this is a less critical factor and requires a second set of trials.

Conclusion

Option 7 (R500 on tool surface) has been selected as the most suitable tool preparation technique as it is the only option to score consistently well on all evaluation criteria.

Table 51: Decision matrix for various tool release options.

Criteria\Option	1	2	3	4	5	6	7
Ease of release							
Laminate surface quality							
Ease of application							
Complex shapes							
Cost							

A.3: Thin Vertical Infusions: Horizontal vs Vertical Resin Flow

A 6m vertical infusion was conducted using a thin laminate (1 ply Saerflow, 1 ply quadaxial, 0.3m wide) to investigate the effects of a horizontal flow front across the width of the laminate. A single, continuous resin inlet was placed up one side of the laminate, and a vacuum outlet across the opposite side. The resin bucket and vacuum pump were placed at ground level. Resin was drawn across the width of the laminate. Figure 141 shows the setup of this infusion and the flow front mid-way through the process.

It was found that the resin flow speed across the laminate was dependant on the height, with the resin flowing faster along the bottom of the laminate compared to the top. This is due to the hydrostatic pressures acting on the resin. As discussed in chapter 4, hydrostatic pressures counteract the vacuum suction, causing a reduction in the overall pressure differential, which in turn results in a slower flow speed. In this infusion the hydrostatic pressure increases with height, causing a gradual reduction in the pressure differential, and hence slower resin flows further up the laminate.

This non-uniform resin flow front may cause problems for larger, thicker infusions such as a 75m hull shell. Faster flow in some regions may lead to resin race tracking and lock-offs. It may be possible to create a uniform flow front by modifying local laminate/sandwich preform permeabilities up the height of the preform. This would be very difficult to do in a robust and reliable manner for thicker preforms such as those featured in the hull shell demonstrator. Furthermore, the height of the hull shell demonstrator is divided into different structural preforms which may infuse at different rates, adding further complexity to the infusion process. Therefore, this infusion scheme does not appear to be a robust option for this case study.

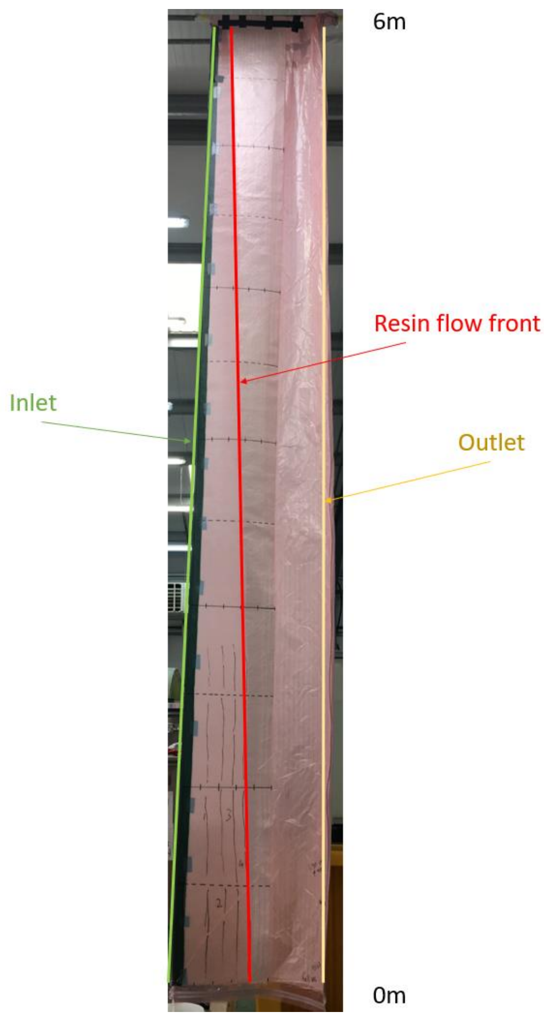

Figure 141: Vertical infusion with horizontal resin flow.

A.4: Thin Vertical Infusions: Upwards vs Downwards Infusions

An alternative scheme whereby resin is infused downwards from the top was also investigated. In this case the resin bucket was maintained at ground level as to not cause vacuum bag ballooning. Two 3m high laminates were infused according to Figure 142 The setup was identical to previous 6m infusions with horizontal inlets every 1m in height. Figure 143 shows the comparison in resin flow speed between top-down and bottom-up infusions.

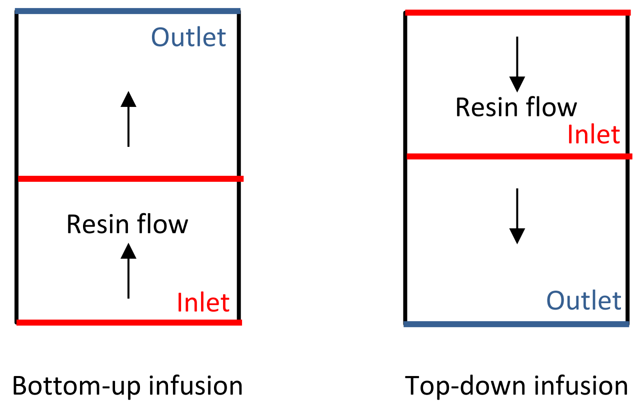

Figure 142: Schematic for bottom-up and top-down thin laminate vertical infusions.

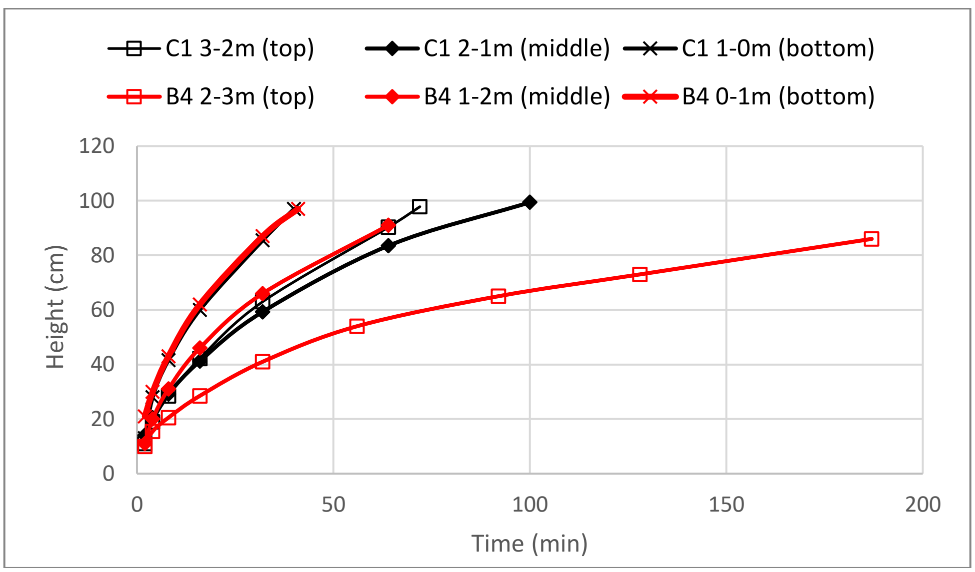

Figure 143: Comparison of resin flow speed between top-to-bottom (C1) and bottom-to-top (B4) infusions. Each infusion is split into three 1m sections (top, middle, bottom).

Figure 143 shows both infusions experience similar resin flow speeds within the middle and bottom sections of the laminate (between 0 and 2m from ground level). However, there is a significant difference in speed of infusion between the two schemes at the 2-3m section, with the top-down scheme being significantly faster. A greater amount of bubbles was observed in the laminate that was infused from top-to-bottom. This is because the bubbles cannot easily escape ahead of the resin flow front as the buoyancy forces act to pull the bubbles upwards, behind the resin flow front. Despite the potentially faster infusion, a top-to-bottom infusion is not considered feasible due to the greater quantity of bubbles.

A.5: Elium vs Epoxy Laminate Impact Test Results

This section describes the impact tests performed by the author that are referenced in Chapter 2. The purpose of this short investigation is to compare the impact response of two resins, and thus demonstrate how resin selection can affect the in-service performance of marine laminates.

Two sets of 10mm thick composite laminates were manufactured by the author and tested using an Instron Dynatup 9250HV drop tower in accordance with ASTM D7136 (ASTM, 2012). A 16mm diameter hemisphere impactor with a smooth circular surface and a mass of 3.29kg was used for all impact tests. Both sets of laminates were manufactured with a layup sequence of [+45/-45/0/0/90/0/0/+45/-45/0]s, which was selected to be representative of a tidal turbine blade skin. The laminate thicknesses and stacking sequences deviate from the standards provided in ASTM D7136. Set A was manufactured from Proset 117/M2010 epoxy resin and 600gm unidirectional Advantex glass fibre (FGE708), whilst set B was manufactured from Elium 180 resin and 600gsm unidirectional Chomorat glass fibre (BT640). Three specimens were tested in each set, with each specimen being exposed to a single 20J and 40J impact. All specimens were clamped to the impact platform on both sides. The author attempted to inspect the impacted specimens using an ultrasound C scanner, however the high thickness and significant surface roughness of the specimens resulted in high levels of signal scatter, and thus a lack of any meaningful results. Table 52 displays a summary of the data recorded during the impact tests. The data indicates that the two sample sets experienced similar impact energies and velocities. The total energy absorbed by the laminate is primarily dissipated via damage formation within the laminate (Liu, H., et al., 2018). Both laminates experience similar levels of absorbed energies for the same impact energies. Figure 144 and Figure 145 display the force-time history for the Proset samples at 20J and 40J respectively, whilst Figure 146 and Figure 147 display the force-time history for the Elium samples at 20J and 40J respectively. All force-time history plots presented show an initial force peak and subsequent reduction in load. This point indicates a change in the stiffness response of the laminates, which is due to the formation of significant levels of damage within the specimen (Liu, H., et al., 2018) (ASTM, 2012). The

Table 52: Impact test data summary

Specimen ID	Impact energy (J)	Total absorbed energy (J)	Impact velocity (m/s)
Proset 1 20J	19.43	16.68	2.23
Proset 2 20J	19.14	16.30	2.21
Proset 3 20J	19.48	16.45	2.23
Proset 1 40J	39.31	33.58	3.17
Proset 2 40J	38.85	33.15	3.15
Proset 3 40J	39.29	33.73	3.17
Elium 1 20J	19.38	17.28	2.23
Elium 2 20J	19.38	17.09	2.23
Elium 3 20J	19.17	16.54	2.22
Elium 1 40J	39.06	33.60	3.16
Elium 2 40J	39.03	33.47	3.16
Elium 3 40J	39.05	33.50	3.16

Elium specimens exhibit a higher initial peak of 14kN to 15kN compared to 8kN for the Proset samples. This could indicate that the Elium laminates are able to withstand higher impact energies prior to the formation of significant levels of internal damage. However, further testing is suggested (including compression after impact) to better understand how this damage affects the laminates' performance.

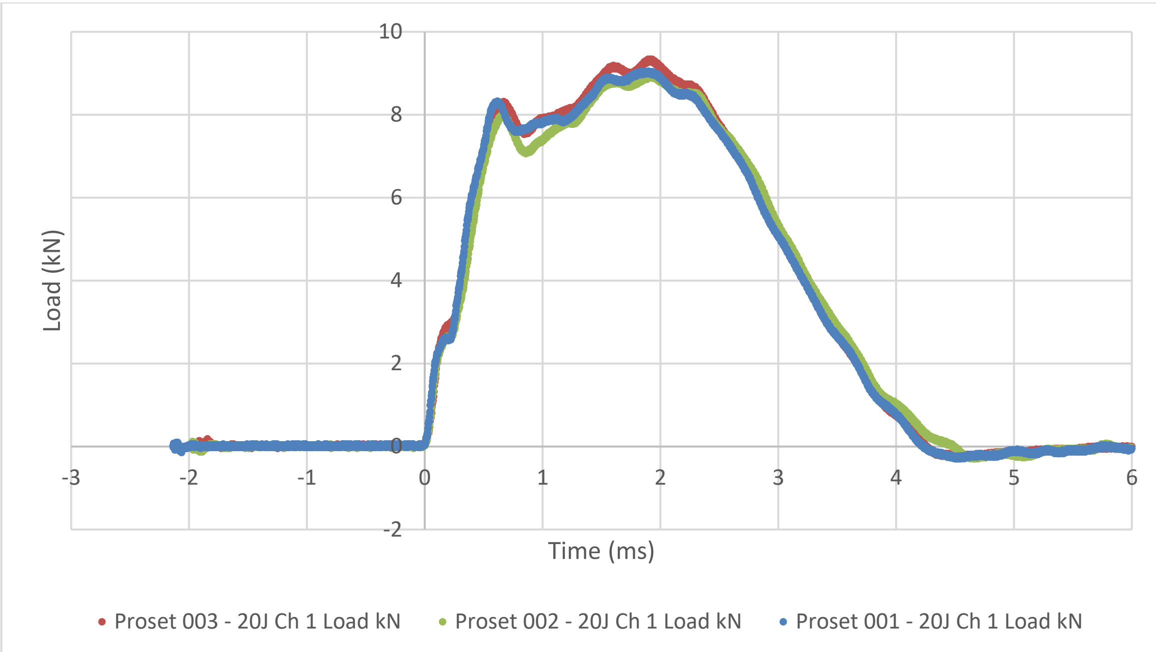

Figure 144: Load vs Time Impact Plot: Proset 117/M2010, 20J Impact

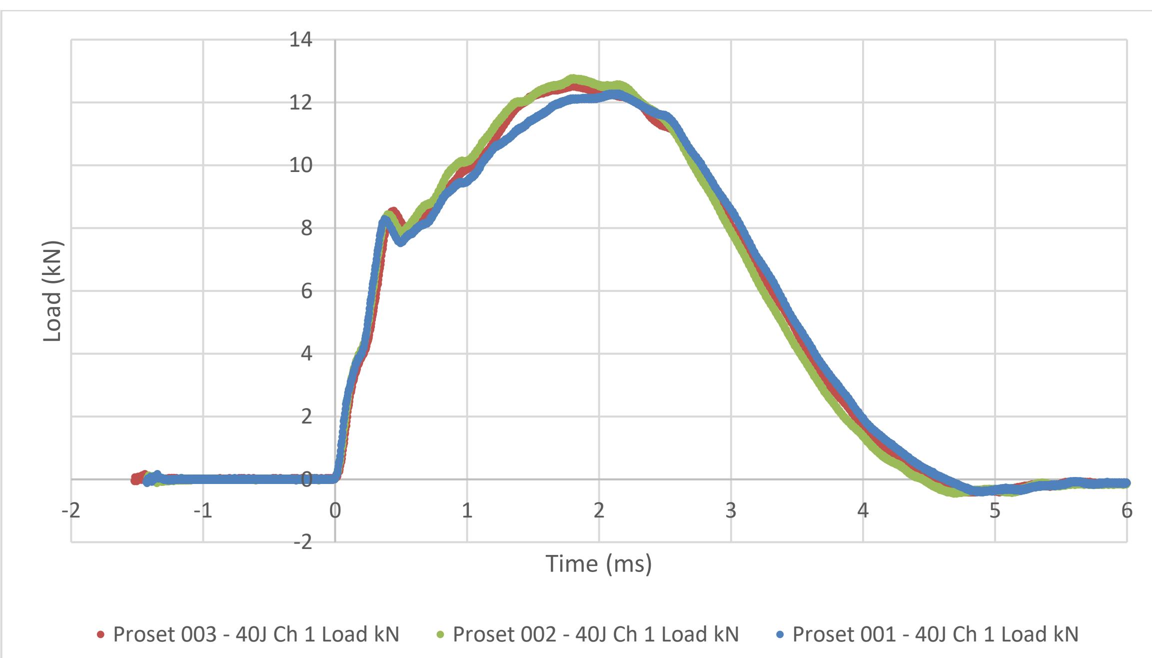

Figure 145: Load vs Time Impact Plot: Proset 117/M2010, 40J Impact

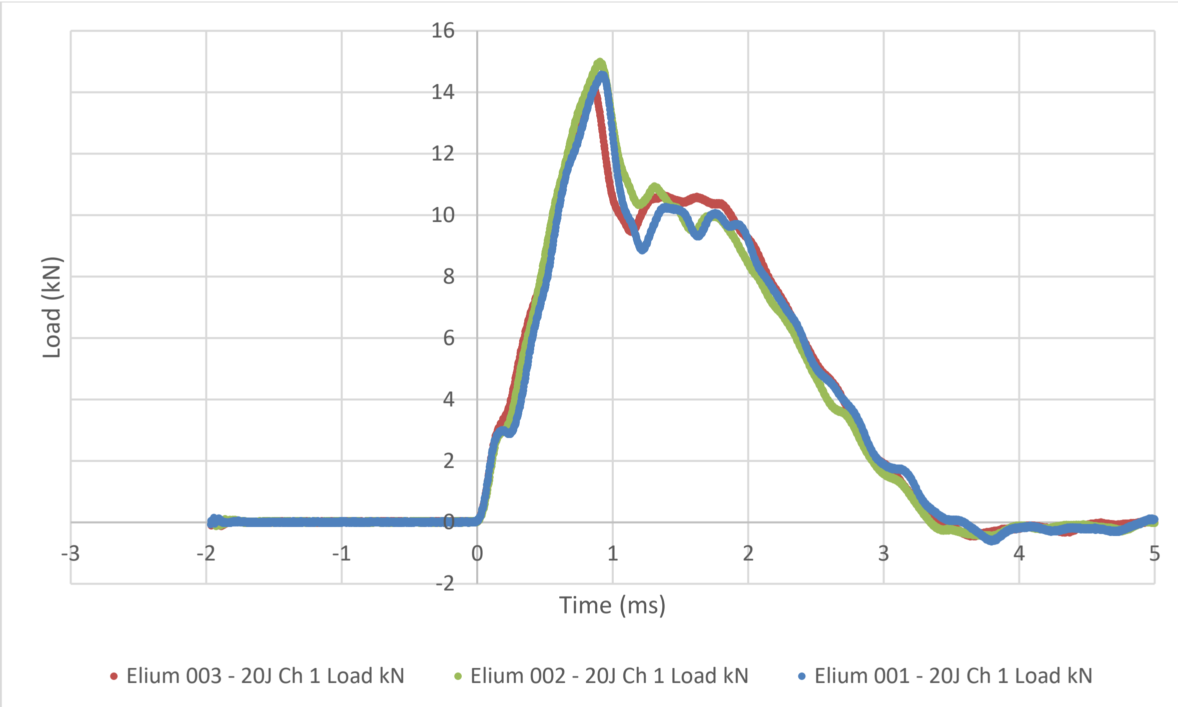

Figure 146: Load vs Time Impact Plot: Elium 180, 20J Impact

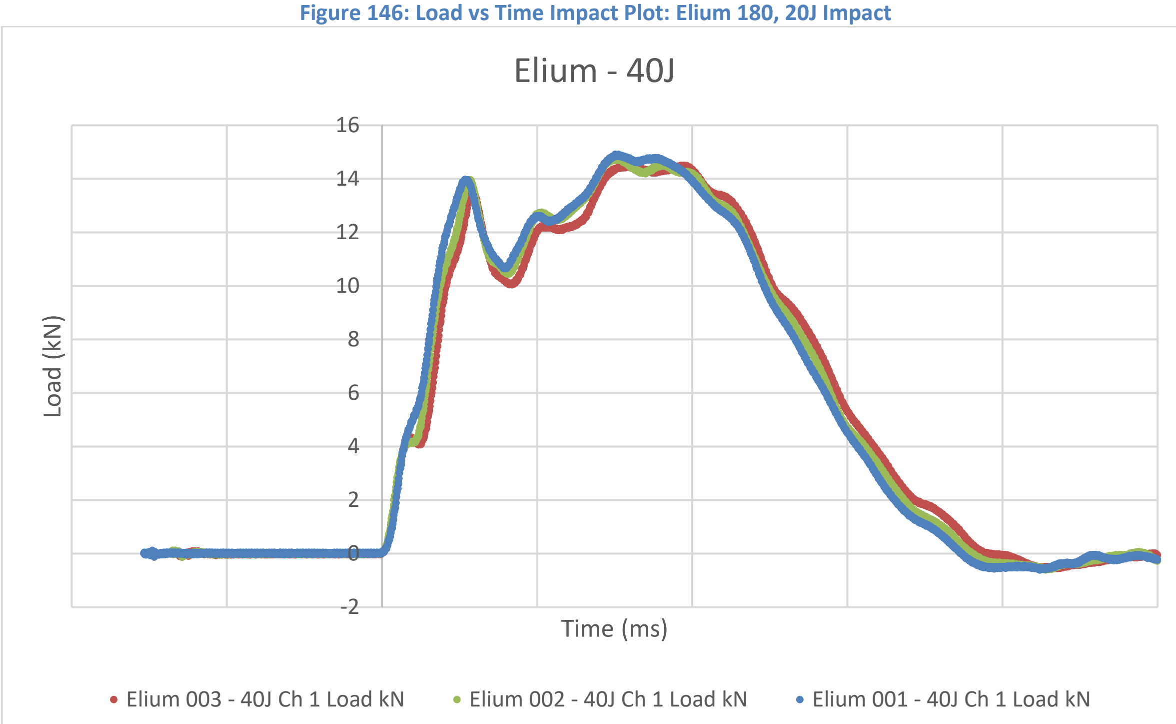

Figure 147: Load vs Time Impact Plot: Elium 180, 40J Impact

A.6: Infusion trials to compare different types of flow media

A number of small-scale infusion trails were conducted to quantitatively compare the resin flow speed across three different types of commercially available flow media materials. Flow media is used in the production of large infused composite structures to improve average resin flow rate throughout large and/or thick preforms. Saerflow, Unifilo and G-flow were considered in this study. Narrow laminate strips (0.15x1m) were infused along the 1m direction. The laminates consisted of 1 ply Saertex 1200gsm quadaxial glass reinforcement and 1 ply flow media. All laminates were laid up on a pre-released aluminium tool surface and infused with Albidur 3.2 resin. Control laminates were also included (1 ply quadaxial only, no flow media) to demonstrate the benefits of flow media vs standard laminates. Infusions were conducted with a vacuum level of -0.9bar at 20°C. Three infusions were conducted for each material. The flow front positions were periodically marked on the bag surfaces throughout the infusions, which were later used to measure the flow front distance from the inlet at specific time intervals. The time to full wet-out each laminate was also recorded. Figure 148 below shows examples of some of these infusions, displaying the infusion setup and flow distance measurements. Due to slight variations in layup (local permeabilities) and infusion setup (inlet positions), the flow front shape can vary between infusions (as shown by the black lines in Figure 148). Some flow fronts appear straight, whilst others are curved. Some level of experimental variation is expected, as these features do not appear to significantly affect the accuracy of the results. Results indicate that G-flow provides, on average, the fastest resin flow rate whilst Unifilo provides the slowest flow rate. All flow media are shown to significantly increase the resin flow rate compared to laminates with no flow media. Without flow media, it was not possible to fully infuse a 1m strip of reinforcement with the Albidur 3.2 resin before gelation had occurred (2.5 hours).

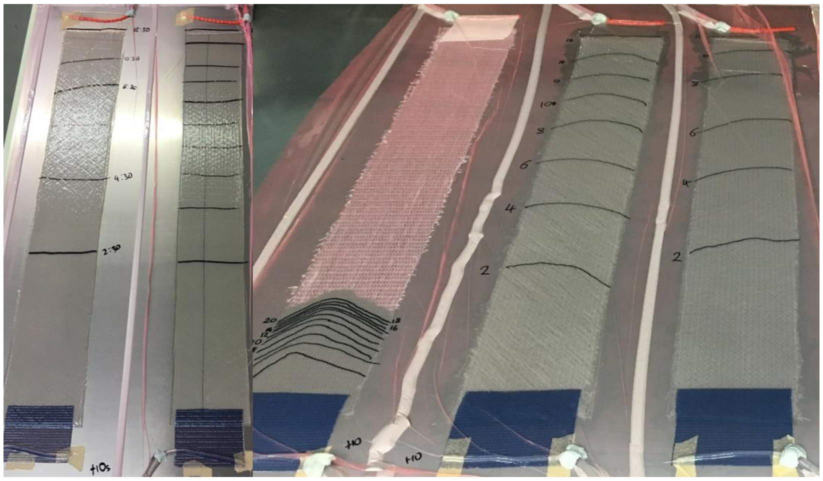

Figure 148: Examples of infusion trials to compare different types of flow media. Left to right: Saerflow, G-flow, Control (no flow media), Unifilo, Saerflow.

Table 53: Comparison of infusion times for different types of flow media

Trial Number	Time to fully wet-out laminate (mins)			
	Saerflow	Unifilo	G-flow	Control
1	13.25	18.25	7.25	N/A
2	10.5	14	8	N/A
3	12.5	16	8.5	N/A
Average	12	16	8	N/A

A.7: Materials cost estimate for 75m hull shell production

The total materials costs were estimated based upon the quantities of materials used to manufacture the demonstrator section, scaled up to the full 75m symmetric hull shell. This estimate assumes a symmetric 75m hull shell of constant cross section, with no bow or stern. Rough material unit costs are provided based upon industrial estimates. A conversion rate between Euro to GBP of 1.14 was used in these calculations as this was the average conversion rate at the time of conducting the research. A unit cost of 10 Euro/m^2 was used to calculate the cost of infusion consumables. This is a rough figure based upon experience and previous commercial projects.

Table 54: Estimated total materials cost for 75m composite hull shell production

Material	total area (m^2)	Volume (m^3)	Areal weight (kg/m^2)	Density (kg/m^3)	Mass (kg)	Unit cost (£/kg)	Total cost (£)
Glass reinforcement	83478	-	1.2	-	100174	2.54	254828.38
Foam core GR200	1936	97	-	200	19356	7.80	150942.84
Foam core GR135	984	49	-	135	6640	7.80	51780.16
Resin	-	65	-	1100	71739	4.39	314645.31
Infusion consumables	1350	-	-	-	-	-	11842.11
Total*	-	-	-	-	-	-	**784038.79**

**Total cost rounded to nearest £1000 when used to calculate ROM production cost estimate*

A.8: Test coupon failure examples

This section provides visual examples of the failure modes observed whilst testing the range of dry and conditioned composite laminates during the durability study. All data included in the thesis was extracted from coupons that failed in the following manner. These failure modes are defined as acceptable for three-point bend interlaminar shear and three-point flexural tests based upon the criteria outlined in ASTM D2344 and ASTM D7264 respectively (ASTM, 2013) (ASTM, 2015).

Interlaminar shear failure mode

Coupons failed in interlaminar shear along the mid-thickness plane between the central loading pin and one outer loading pin. No flexural failure or crushing under the central pin was observed in any of the specimens.

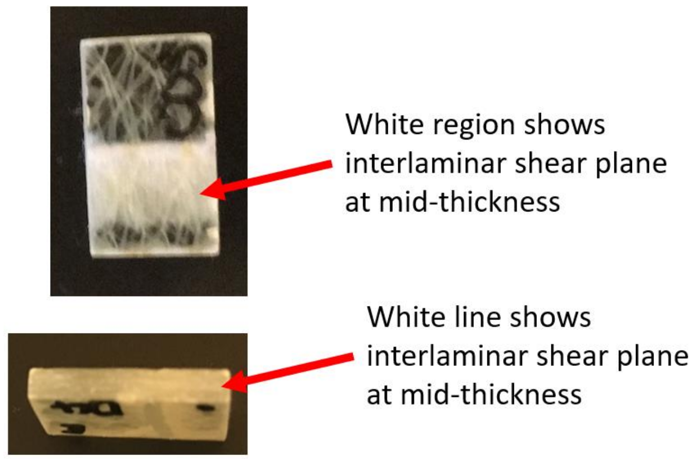

Figure 149: Interlaminar failure mode

Flexural failure modes

Coupons failed via ply buckling in the middle of the specimen under the central loading pin. Buckling resulted in or was preceded delamination of the outer ply on the opposite face. No interlaminar failure or crushing under the central pin was observed in any of the specimens.

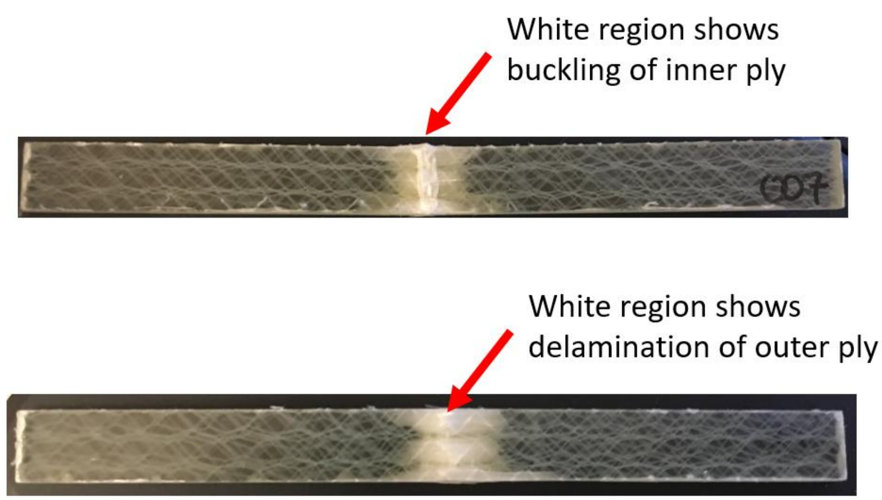

Figure 150: Flexural failure modes