INVESTIGATION OF VARTM RESIN FLOW THROUGH 3D NEAR NET–SHAPE AEROSPACE PREFORMS

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ABSTRACT

Prepreg-based processes for autoclave PMC manufacturing are the default options for complex structural aerospace carbon epoxy structures due to the high specific stiffness and strength of PMC parts and structures made from these processes. Furthermore, the high reproducibility of prepregs and of the parts produced combined with well-documented production processes are highly sought-after by industry to facilitate certification. However, prepreg-based manufacturing routes expensive due high operating costs of autoclaves, which are seeing intensive usage nevertheless and limited worldwide capacity. Vacuum Assisted Resin Transfer Moulding (VARTM) offers an interesting alternative for manufacturing near net-shape components at reduced cost by doing away with autoclave cure and refrigerated storage of precursor materials.

Reproducible VARTM production of parts with complex geometry and low void content is highly dependent on the kinetics of the flow of resin into preforms upon infusion and on the adequate design of infusion systems for speed, consistency and thorough impregnation. This work presents an overview of experimental trials where VARTM infusion through carbon fibre textile preforms and equivalent glass fibre textile preforms of varying geometric complexity was probed using different gating configurations, with the aim of designing a robust production process along the lines stated above. Trials were conducted using silicon oil infused through glass and carbon fibre preforms, enabling the capture on camera of evolving flow fronts through translucent 3D cavities for flat panels, panels with a single T-brace and panels with a double T-brace. The trials covered the effects of preform geometry, preform construction and stitching, and port and vent location on resin flow.

1 INTRODUCTION

This work was conducted as part of project CRIAQ COMP-501, which aimed at developing manufacturing methods suitable to the production of complex 3D preforms and composite parts using liquid processes, aiming at final properties similar to those of existing prepreg constructs. The geometry of the parts and demonstrators was generally representative of existing structures certified for civilian air travel. Manufacturing using prepreg is inflexible and incurs high costs; chief among those are autoclave curing and the need to keep the prepreg refrigerated to impede reticulation of the polymer until required. The selected 3D part geometry was a panel with integrated physical stiffeners in the form of secondary stiffener plates extending at 90° from a main plate. Such stiffeners increase the second and polar moments of inertia with little penalty in terms of added mass. With traditional materials and construction methods, these stiffeners are either bolted or welded to the main structure. Such assembly methods are problematic for composite parts as they require additional, delicate and potentially damaging drilling operations along with the use of fasteners featuring different coefficients of thermal expansion than those of the structure. It is much preferable to produce composite panels with integrated stiffeners, as single items. The research work presented in this article aimed at investigating and understanding resin flow, in cases of increasing complexity, culminating with such panels featuring integrated stiffeners.

VARTM processes have generally been associated with the production of flat plates or simple shell geometries and therefore, flow patterns through complex 3D preforms are not well known. The central aim of this research was to evaluate and improve manufacturing process for stiffened panels made from complex preforms assembled by stitching and tufting, with a focus on resin flow kinematics. The research was planned in 3 different experimental phases determined by individual and sequential goals. Test rigs were designed and built for each phase, and used as described below.

The first phase aimed at quantifying the permeability of textile stacks and at determining the feasibility of replacing carbon preforms with suitable glass fibre equivalents for investigating resin flow kinematics in subsequent phases. The effects of stitching on flow fronts and on permeability were analysed. Furthermore, 3D carbon woven textiles were tested to assess whether their permeability values were comparable to the current preforms made using 2D weaving techniques. Such textiles could potentially be used to further simplify the manufacturing of parts of complex geometry.

The second phase aimed at testing the effects of part geometry and of inlet and outlet locations on resin flow kinematics. The tests were also used for demonstrating repeatability and for probing further the effects of stitching on resin flow in critical locations.

The final phase aimed at simulating the high temperature infusion of a full scale demonstrator and at troubleshooting the process developed in collaboration with industrial and academic research partners in CRIAQ COMP-501, on a corresponding metal mould. Effects of stitching the preform on moulding and infusion time were noted and compared with times obtained for non-stitched preforms.

2 EXPERIMENTAL SETUP AND PROCEDURES

In the interest of quantifying textile reinforcement permeability and resin flow through assembled preforms for stiffened panels, three flow testing rigs were used with reinforcements and preforms. Two of these rigs were designed and built by the author specifically for the geometry studied.

Rig #1 enabled permeability trials to be conducted on flat stacks of reinforcements and preforms leading to a quantitative evaluation of permeability. This first rig is referred to as the permeability rig hereafter. Rig #2 was designed for viewing resin flow fronts in a smaller section (200 mm x 200 mm) of a single T-stringer and for evaluating the effects of different inlet and outlet positions. The second rig is referred to as the translucent cavity rig hereafter. Rig #3 was effectively designed as a translucent mould which replicated the injection of full scale demonstrators (1.2 m x 0.6 m) featuring two integrated stiffeners, corresponding exactly to actual composite demonstrator parts produced by the COMP-501 research team. This third rig is referred to as the demonstrator rig hereafter. Trials were separated into 6 series labeled T1 through T6, as presented in Table 1.

Table 1: Trial Series

Trial Series	Rig	Intent
T1	Permeability	Permeability of Preforms
T2	Translucent Cavity	Testing Mould and Manifold
T3	Translucent Cavity	Effects of Inlet Locations
T4	Translucent Cavity	Effects of Preform Assembly
T5	Translucent Cavity	Validation of Demonstrator Geometry
T6	Demonstrator	Full Scale Demonstrator

Each trial series subdivides into further sub-series of tests executed on the various preforms, as detailed in Table 2. The sub-series are given a numerical identifier in the form T1-C# where T1 represents the primary trial series and C is the material or other defining characteristic, followed by an exclusive digit.

Table 2: Detailed Trial Series

Rig	Trial Series	Tests	Repeats
Permeability	T1	Baseline Carbon Quasi (T1-C#)	1
		Stitched Carbon Quasi 4mm pitch (T1-C#)	3
		Stitched Equivalent Quasi 4mm pitch (T1-EG#)	2
		3D Woven Carbon (T1-W#)	3
Translucent Cavity	T2	Plain Weave Glass – Lockstitch (T2-G#)	3
	T3	Mod Equivalent Quasi – Lockstitch (T3-MEG#)	8
	T4	Interlocking – OSS (T4-S#)	3
		Tufting Through Filler (T4-T#)	3
	T5	Carbon Quasi OSS 4mm Pitch (T5-C#)	1
Demonstrator	T6	Glass Demonstrator No Stitch (T6-BGF#)	2
		Glass Demonstrator OSS (T6-MEG#)	1
Total			33

2.1 Textile Reinforcements and Preforms

Preform stacking sequences were defined by the industrial partners to meet stiffness requirements along the 0^o axis, of which three types of stacking sequence were identified, Table 3. All stacking sequences featured 0/90^o and ±45^o plies of twill fabric. Once flat plate sample tests were conducted by C. Leduc [1] early on in the COMP-501 project, the need to focus on a single stacking sequence was recognised. Selecting 1 type of preform and stacking sequence negated the need for generating multiple baselines for analysis. The Quasi stacking sequence was selected as the more isotropic preform with regards to the effects of stacking sequence on flow, as well as for its mid-range material properties in the final composite part.

Table 3: COMP-501 Definition of Laminates Considered [1]

Laminate	Stacking Sequence	AML
Soft	$[((\pm45)_2/(0\text{-}90)/(\pm45)_2)_2]_S$	70
Quasi	$[((\pm45)/(0\text{-}90))_5]_S$	25
Hard	$[((0\text{-}90)_2/(\pm45)/(0\text{-}90)_2)_2]_S$	-20

Preforms of various types were manufactured from fabrics provided by Texonic for demonstrator development. The primary carbon fabric used in this work was TC-06-T, a 2x2 twill woven made of Toho Tenax HTS40 E13 3K 200 tex yarns with total surface 31 density of 205 g/m^2 (6.0 oz/yd^2). To help visualising flow in the rigs and to reduce cost, glass fabrics were used in performing many injections. The main glass fabric used as replacement to its equivalent carbon counterpart was Texonic TG-09-T, a 2x2 twill woven made of AGY E-glass 245 tex yarns with total surface density of 315 g/m^2(9.3 oz/yd^2). Secondary glass fibre fabric BGF 1800 purchased through Composites Canada and used for producing the larger demonstrator preforms, was a plain weave of ECK 18 1/0 yarns with total surface density of 326 g/m^2(9.6 oz/yd^2).

Preforms were to be stitched and/or tufted; both techniques were considered for potentially increasing resistance during tear-out tests on composite parts where stiffeners are concerned, and for easing the handling of dry preforms. Another textile was proposed by CTT group in the form of a 3D woven reinforcement produced as a single part that would match the *x* and *y* yarn densities of the Quasi preforms, Figure 2-1.

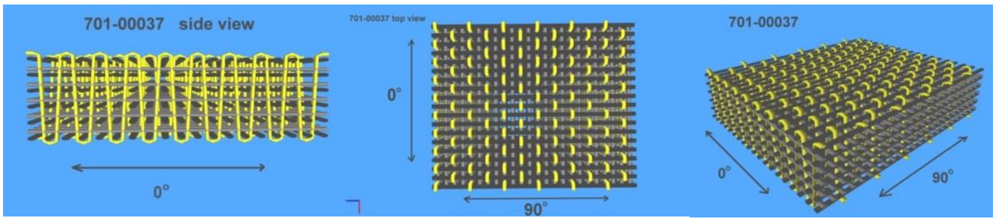


Figure 2-1 NCS 11 Ply 3D Carbon Weave (701-00037)

As stitching or any form of through-thickness reinforcement would be mostly perpendicular to the flow front, it was deemed important to quantify the effects that such structures may have on overall infusion patterns. Therefore, in addition to quantifying the permeability of the textiles used in their actual stacking sequences, a secondary aim of this work was to evaluate the effects of through-thickness reinforcements on the flow properties in the context of the COMP-501 project.

CTT group provided preforms assembled using one-sided stitching (OSS), a technique developed by Keilmann Sondermaschinenbau GmbH (Lorsch, Germany) which uses a single multi-axis robotic stitching head and removes the need for the underside mechanism usually associated with stitching machines. Figure 2-2(a) shows the thread pattern as seen from the stitching head side; the preform is not shown for clarity. Figure 2-2(b) illustrates the needle arrangement. In all preforms provided by CTT group the catcher needle was oriented at 45° from the vertical and the stitching line was 25 mm (1 in) wide. In permeability trials (T1) the pitch was 4 mm while on all remaining OSS preforms it was 8 mm. The thread used for all OSS was 67 x 2 tex (linear mass of 0.14 g/m) TENAX® carbon fibre yarn.

During the construction of preforms including stiffeners, ply stacks were bent to form a new plane perpendicular to the first. In doing so, the ply stack will bend to a radius and thus leave a zone devoid of reinforcements at the intersection. Such zones must be filled with reinforcement fibres to prevent a dramatic reduction in v_f of the stacks themselves through their inevitable sagging into the void, and also to prevent the formation of a large resin rich section in the preform. Fibers used for filling such zones are called fillers. Three different types of fibre assemblies were used as fillers in this work. Filler type #1 featured 6 strands of E-glass yarn, each with a linear density of 4.5 g/m twisted 1 full rotation over the length of the preform, providing a nominal v_f of 61%. Filler type #2 featured 22 strands of Tenax-J HTS40 E13 12k 800 tex carbon yarn twisted 1 full rotation over the length of the preform, providing a v_f of 55%. Filler type #3 was the AERO BIB 2005 ±45° braided Tenax-J HTA40 E13 carbon strand purchased from Eurocarbon BV providing a v_f of 53%, Figure 3.5.

The flat plate permeability rig of test series T1 required square preforms measuring 300 mm (12 in) in length and width. Once calibration procedures were completed, testing was conducted on CTT group preforms. Cavity thickness was adjusted to 4.2 mm through the use of shims for tests conducted on Quasi, Equivalent Quasi and 3D Weave preforms. The stitched preforms featured a single centrally located OSS line with a 4 mm needle pitch and a standard 25 mm width as seen in Figure 2-4(a).

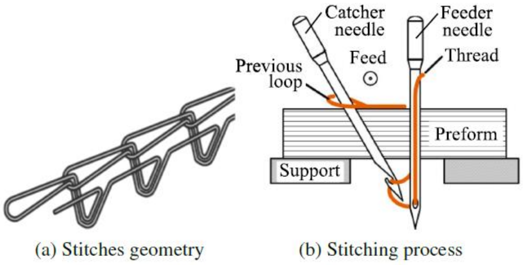


Figure 2-2 Machine One-Sided Stitching

Test series T-2 through T-5 preforms shared the same final dimensions dictated by the rigid nature of the Translucent Cavity, although their construction and assembly differed. The preforms consisted of a skin and a perpendicular sail. The skin of the stiffened panel was a square with sides measuring 203.2 mm (8 in) and 4.2 mm in thickness. The sail material was split down its centerline and bent to form the foot which was in contact with the skin. The foot extended by 50.8 mm (2 in) either side of the sail centerline, while the sail extended by 46.6 mm from the skin's contact surface to the tip. The inner radii formed by this bend measured 4.2 mm, equal to the initial target thickness of a Quasi preform.

Tests performed in series T2 and T3 involved a lockstitch sewing pattern as shown in Figure 2-3 and positioned on the preforms as per Figure 2-4(b). Tests performed in series T4 and T5 used OSS preforms provided by CTT group and stitched as indicated in Figure 2-3(c), with the exception of series T4. Test series T4 aimed at determining the effects of stitching and tufting in the immediate area of the filler, and at investigating whether filler v_f and construction affected macroscopic flow through the preforms. As illustrated in Figure 2-5, the CTT OSS perforated the filler or displaced material on its fringe while tufting directly penetrated the filler and in some cases the sail.

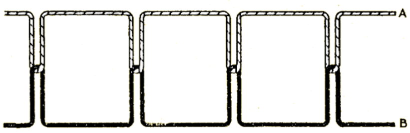


Figure 2-3 Lockstitch Geometry [2]

2.2 Experimental Setup

2.2.1 Permeability Rig

The cavity of the flat plate permeability rig consisted of an aluminium base, a translucent polycarbonate cover, spacers and steel braces. The base was an aluminium square plate measuring 406.4 mm to a side and 25.4 mm in thickness, with a central inlet port. The cover was a 12.7 mm thick sheet of polycarbonate with outer dimensions identical to those of the aluminium base, and corresponding bolt holes. Pressure at the inlet was recorded with 2 pressure transducers while the silicone oil was driven at a steady rate by a hydraulic cylinder actuated by a 4482 screw-driven Instron universal testing frame. Results are analysed using Darcy's Law for either isotropic or orthotropic cases using the pressure and video data [3,4] .

2.2.2 Translucent Cavity Rig

A 300 mm x 300 mm x 200 mm, 3-part translucent PMMA cavity with interchangeable inlet and outlet ports was designed and built for exploring the effects of multiple inlets and outlet port locations on resin impregnation and flow. The cavity, seen in Figure 2-6 was sealed using steel braces and carriage bolts.

As shown in Figure 2-7, the configuration on the top plate featured three ports (P1, P2, P3) lined to one side, one port at the midpoint of the skin (C), and one port connected to a 3 mm (1/8 in) line milled 2 mm deep on the opposite side (L). The 3 final ports were located at the tip of the sail, at the corners and center (SP1, SP2, SP3). Camera 1 was setup to capture the infusion from the top of the Translucent Cavity, filming the skin of the preform, while camera 2 and camera 3 where on either sides of the mold for capturing flow evolution through the sail. The principal quantitative result which was used for comparison is the completion time of an infusion.
This completion time may be either to the complete impregnation of the preform or to the stoppage of the trial by the author. The full impregnation or, in the opposite case, the existence of voids and dry locations following completion of a test was also noted and compared. General flow kinematics and occurrence of major events were also detailed in a log adjoining each test and in a flow progression graphic.

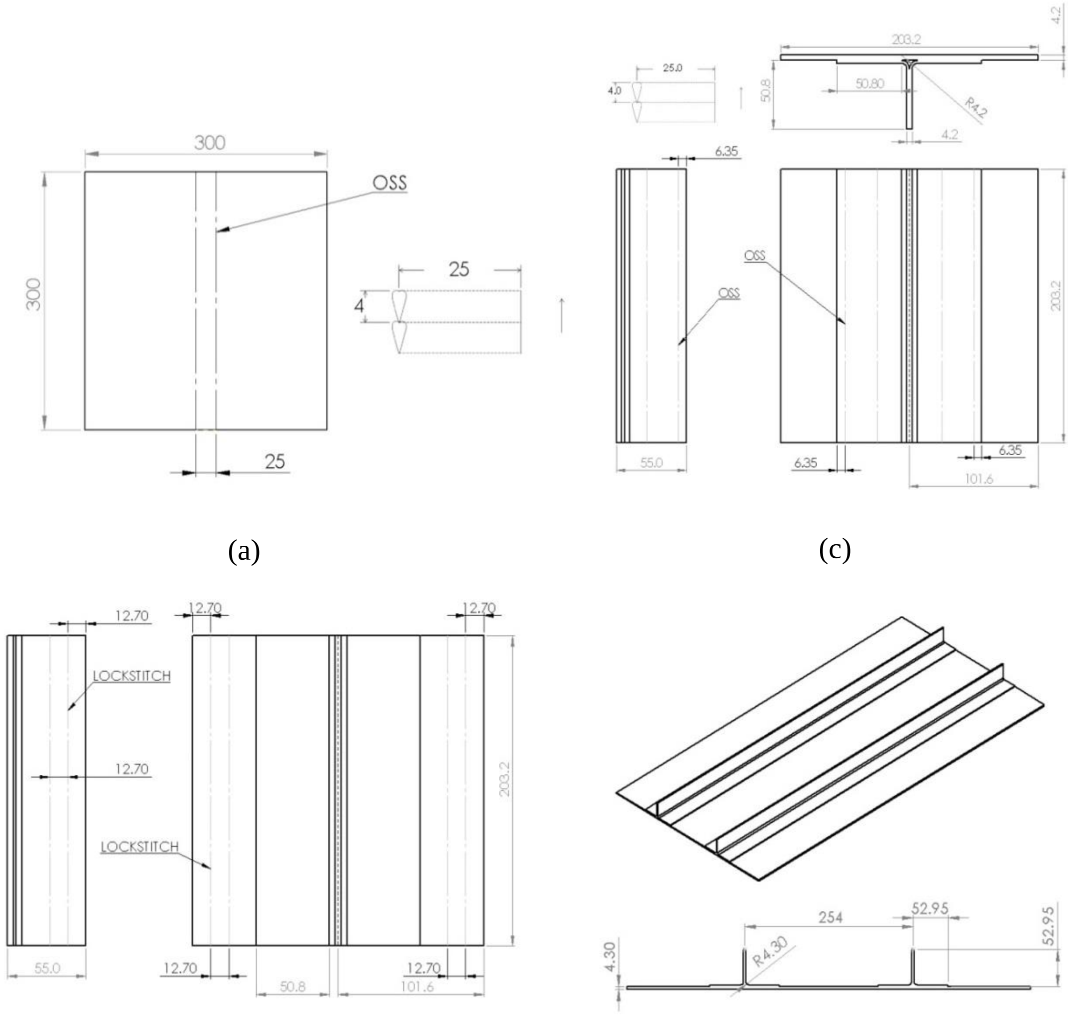


Figure 2-4 Preform Diagrams

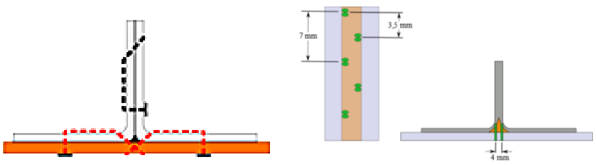


Figure 2-5 Stitching Through Filler and Tufting

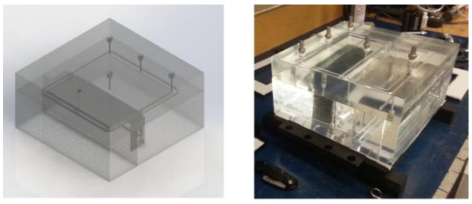


Figure 2-6 Translucent Cavity Render and Rig

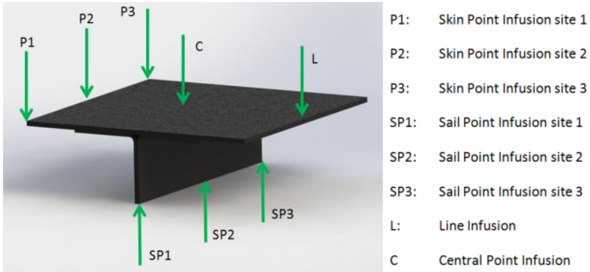


Figure 2-7 Inlet Locations on Translucent Rig

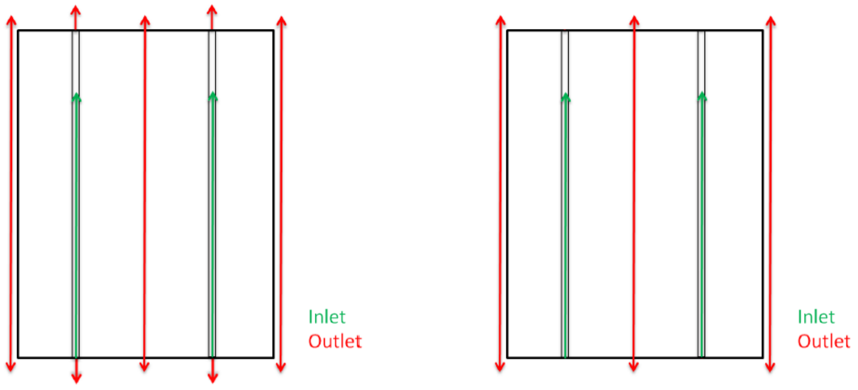
2.2.3 Full Scale Demonstrator

The primary component of the Full Scale Demonstrator Rig was a 25 mm thick base PMMA plate measuring 1524 by 813 mm (60 x 32 in) onto which the main panel of the dry preform was laid down, allowing visualizing and capturing of simulated resin flow through this base plate, as well as 2 sets of 2 PMMA triangular cross-section braces measuring 1321 mm in length (52 in). The PMMA base rested on a steel frame set on coasters, and the braces were attached to the base. Figure 2-8 shows a CAD rendering and the final rig.

Figure 2-8 Full Scale Demonstrator Rig

The braces replicated aluminium tooling used by COMP-501 partners for moulding carbon fibre preforms at high temperatures. As such, additional steel stiffeners were mounted in the PMMA braces increasing their bending stiffness. The braces were made from three layers of 25 mm thick PMMA plates 75mm x 1525 mm glued with #16 weld-on acrylic glue using a wooden press made by the author and then machined to final finish by University technicians.

Two manifolds machined by the author were used for controlling outlets during infusions. They were milled out of aluminium bars to allow up to 5 different outlet lines to culminate into a single tube. The manifolds allowed the Full Scale Demonstrator Rig to infuse preforms from a variety of directions; only two of these were used in this work, Figure 2-9. Type #1 infusion featured inlets from a single side through the whole length of the sails with vacuum drawn from spiral tubing on either side, center of the preform and at the point of contact between the sail and the skin through the filler. Type #2 infusion featured the same inlet setup but line outlets only on the sides and center of the preform. Camera 1 was used on a tripod for filming the infusion from above, while camera 2 was used for filming from underneath from the shelf. Camera 3 located on a tripod from the side was used for capturing the flow evolution in the vertical sails.



(a) Type #1: Outlet at noodles, sides and center (b) Type #2: Outlet at sides and center

Figure 2-9 Full Scale Demonstrator Inlet Outlet Configurations

3 RESULTS

3.1 Permeability Results

The preforms tested with the Permeability Rig in trial series T1 were mainly isotropic; permeability values appear in Table 4. From these values, we can see that the permeability of stitched carbon preforms and selected glass equivalents are extremely close, and thus the latter proved an adequate substitute. The permeability of the baseline carbon preform is off from that of the stitched preforms by a factor of 2.83 which could mean that stitching increases the permeability accordingly. Else, a larger sample size may have reduced this deviation since variability on permeability values is notoriously high. The evaluation of various stitching arrangements tested over the course of this thesis seems to confirm the findings of Song [5], in which the effects of stitching on overall permeability were localised around the immediate stitching region with flow fronts returning to isotropic once the obstacle is cleared, in the case of 2D preforms. There were noted disturbances to the flow regime when the stitching was in a location of varying geometry, such as the interface between the sail and skin.

Table 4: Isotropic Permeability Test Results

Preform	Permeability K(m^2)	Standard Deviation s (m^2)	Standard Error SEK	Sample Size NK
Carbon Quasi Baseline (T1-B)	4.43E-08	8.99E-08	4.64E-09	376
Carbon Stitched Quasi (T1-C)	1.26E-07	2.19E-07	7.30E-09	900
Equivalent Glass Quasi (T1-EG)	1.31E-07	5.64E-08	1.76E-09	1027
Plain Weave 2 Mod Equivalent Quasi (T1-BGF)	3.97E-08	1.99E-04	9.79E-06	415

The 3D woven preforms provided by CTT group proved to have an orthotropic flow pattern, and as such their permeability was presented in a tensor format, Equation 1. Test T1-W1 had a permeability tensor which deviated from the set norm of tests T1-W2 and T1-W3 and hence a second averaged permeability tensors excluding T1-W1 is presented in Equation 2. The standard deviation and error for the orthotropic analysis method are difficult to quantify because of the visual nature of the video analysis, therefore these values were not calculated in this work.

$$[K] = \begin{pmatrix} 1.38 & 0 \\ 0 & 5.78 \end{pmatrix} \cdot 10^{-7} m^2 \qquad (1)$$

$$[K] = \begin{pmatrix} 8.60 & 0 \\ 0 & 39.6 \end{pmatrix} \cdot 10^{-8} m^2 \qquad (2)$$

3.2 Translucent Cavity Results

Trial series T2 through T5 conducted in the Translucent Cavity Rig, allowed for the exploration of multiple inlet and outlet configurations which yielded important information regarding flow behaviour in a complex 3D preform. Trial T2 showed that central infusion ports were not effective in VARTM as the relatively small pressure gradient could not induce enough force into the fluid column to infuse the preform properly. Edge effects were also noted as being a primary concern with this specific configuration. In trial series T3, the comparison was made between line infusions either along or perpendicular to the sail, and infusing from the sail's corner or center. These trials identified once again racetracking as primary concern, but also led to concluding that infusing from the corner of the sail and in a line along the sail's edge had similar effects on the infusion pattern and pocket creation, which is a concern for porosity in the composite part. This information combined with the geometry of the full scale demonstrator prompted the decision to infuse from the center of the sail for future tests in the Translucent Cavity Rig.

Trials T4-S and T4-T investigated the effects of z axis reinforcements in the region of the filler, primarily OSS and tufting. These methods of reinforcement proved to have detrimental effects on the flow properties in the zone of the interface between the sail and skin. The flow front could be directed entirely to one side rather than both upon piercing though the skin. In addition to these findings, microscopy performed on manufactured parts using these same reinforcement methods showed severe porosity in the filler region [6] .

Trial series T5 confirmed that flow behaviour observed in prior tests on equivalent or substitute materials was indeed representative of the flow behaviour with the final stitched configuration of carbon preforms. In addition to identifying the best approach to manufacturing, these tests provided valuable experience relating to the management of inlets and outlets, and to the effects that closing or modulating them could have on an infusion.

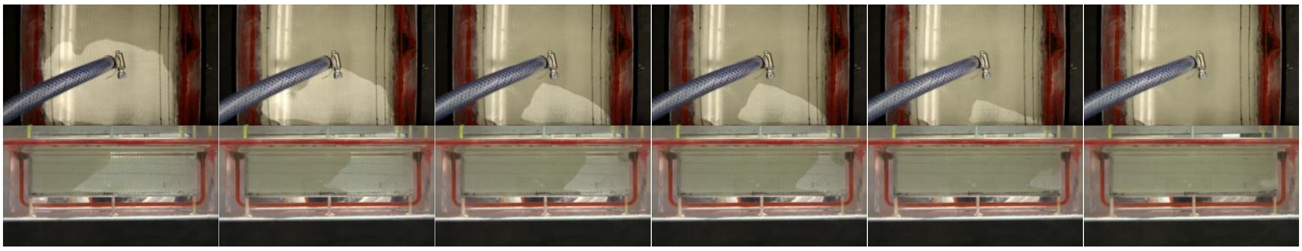


Figure 3-1: Translucent Cavity T2-G1 Flow Evolution

3.3 Full Scale Demonstrator Results

In test series T6, 3 full scale glass fibre demonstrators were infused and various inlet and outlet configurations were tested as well as their layout about the preform. The use of needle valves proved to be unsatisfactory and led to the formation of visible voids in both the first test (T6-BGF1) and an equivalent infusion on a composite part by partners at ETS. The second test (T6-BGF2) demonstrated the need to have access to the infusion equipment and for continuous surveillance of the process as once the leak was detected and rectified, the infusion was completed successfully. The use of clamps was deemed preferable to that of needle valves in both controlling inlet flow as well as closing outlets which have seen their effective preform region fully infused. The final test (T6-MFG) showed the possible downside to using clamps to modulate inlet flow with rigid tubing with the tube collapsing and restricting the inlet flow. In addition it was found that outlet spiral tubing should extend along the whole of the preform to reduce the effects of preferential flow.

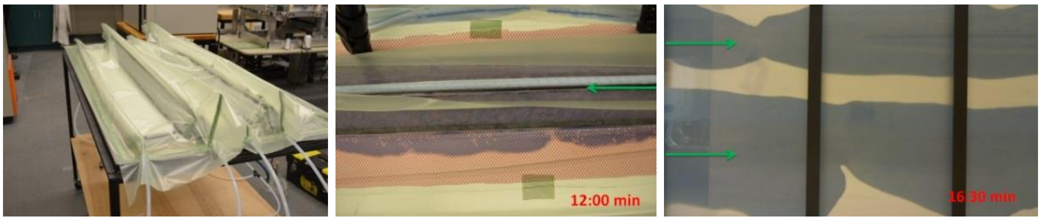


Figure 3-2: Full Scale Demonstrator T6-BFG2 Flow Evolution

4 CONCLUSIONS

Results from flat plate permeability trials demonstrated that stitching only impacts local permeability and as long as the stitching volume is low in comparison to the preform effects on flow kinematics were negligible. The translucent cavity trials demonstrated that stitching and tufting reinforcement in the varying geometry zone had severe adverse effects to the flow kinematics and to the final part porosity levels. These trials in conjunction with the final demonstrator geometry advised the choice of inlet and outlet arrangement for the full scale demonstrator. The final trial series uncovered possible manufacturing complications and contributed to the establishment of infusion procedures for the final COMP-501 demonstrator part.

Difficulties encountered provide an opportunity to improve the methods currently used in the production of composite parts necessitating slower flow fronts. Current vacuum rated adjustable valves are too expensive to qualify as consumables, and most of their inner workings are too complex to protect them from curing resin, rendering them single use items. Their replacement could be an interesting avenue of research, to improve overall control of the flow regime in preforms.

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