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DEVELOPMENT OF A SIMPLE LAB-SCALE VACUUM ASSISTED RESIN TRANSFER MOLDING (VARTM) PROCESS

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ABSTRACT

The goal of the current study was to develop and demonstrate a simple and quick lab-scale VARTM process for the purpose of making flat panels for subsequent characterization, for example in new materials development efforts. This process was not intended to be optimized for final production, rather it served as the quickest way to make lab-scale composite panels using VARTM while maintaining all the salient features of typical VARTM processes used in larger scale manufacturing. There is a wide variety of ways to implement VARTM, as well as a diverse list of potential materials and supplies from which to choose. The process we arrived at was implemented on a 60 cm x 90 cm (2 ft. x 3 ft.) aluminum plate, which was mounted to a moveable cart and intended for ambient temperature processing (no heaters). Details of the vacuum system, resin distribution strategy, and bagging procedures will be described herein. The system was tested by making carbon/epoxy composite laminates of approximately 30 cm x 45 cm (1 ft. x 1.5 ft.). These panels were tested for thickness variation and fiber volume fraction. Optical microscopy was also used to evaluate the microstructure, and limited tensile testing was performed. The results indicated that the panels were of reasonable quality with no significant porosity.

1. INTRODUCTION

The vacuum assisted resin transfer molding (VARTM) process has been used for decades as a low cost process for manufacturing large composite structures. It involves the use of a vacuum bag and one-side tooling only to consolidate a laminate. Interest and use of VARTM in the aerospace, infrastructure, and energy industries has increased over the past two decades [1-3]. In addition, there have been many good studies conducted to develop process models and develop new materials for use in VARTM [4-7]. There are many possible variations of VARTM, which are mostly related to how the resin is brought into the mold and distributed to the composite. Despite some claims that VARTM is an "easy" process, beginners in the field of VARTM usually find it difficult to come up to speed on how to best implement the process for their application. In some cases, users of VARTM are simply trying to evaluate new material systems (resins, fibers, sandwich core materials), and they are not necessarily interested in optimizing the process for a specific application.

The goal of the current study was to develop a relatively easy-to-implement VARTM process for the purpose of making flat panels for physical and mechanical testing. This would support materials evaluation efforts as well was educational programs at our institution.   Although there are numerous publications on VARTM processes in the literature, as well as video media available on the internet, we found it difficult to identify a good reference with detailed instructions for making simple composite structures (small flat laminates, no core). To this end, we used information from various sources, as well as our own experience, to tailor a process that accomplished the following: relatively quick to set up, portable, uniform thickness panel created, and maintains key features of larger scale processes (use of similar flow media, vacuum bags, mold surface, peel plies, etc.). The process described herein was developed during a graduate laboratory course on composite processing and testing, offered at our institution during the spring semester of the past three years.

2. EXPERIMENTATION

2.1 Materials

Two different carbon fabrics of similar areal weight were used in this study: a) woven 5 harness satin (5HS), and b) triaxially braided 0°/±60°, see details in Table 1. These were chosen to evaluate potential differences the fabric architecture would have on the molding results. The 5HS fabric is generally known to be highly conformable and can pack to a high fiber volume fraction (V_f) when making flat plates. The braided fabric had more "open" space and was more "lumpy" than the satin weave due to the braid architecture.   The 5HS material was supplied in a 127 cm (50 inch) wide roll, which was cut into <u>five layers</u> of 30.5 cm x 25.4 cm (12 inch x 10 inch), for a total fiber areal weight (FAW) of 1900 g/m^2.   The QISO material was supplied in a 24.1 cm (9.5) inch wide roll, so it was cut into <u>five layers</u> of 30.5 cm x 24.1 cm (12 inch x 9.5 inch) for a total FAW of 1985 g/m^2.   An additional QISO panel was made with a length of 71.1 cm (28 inches).

Table 1. Fabric characteristics.

Fabric architecture	Supplier	Fiber Areal Weight, FAW (g/m^2)	Fiber composition	Fiber density, ρ_f (g/cm^3)
Woven, 5HS (0°/90°)	BGF Industries Inc., style 94900	380	Hextow AS4C, 6k	1.79
Braided (0°/+60°/-60°)	A&P Technology, QISO AP9048	397	Grafil 34-700, 12k (0°) Grafil TR50S, 6k (±60°)	1.80 1.82

The resin system used in this study was EPON 862 (diglycidyl ether of Bisphenol F) and Epikure 3274 (comprised of about 80% polyoxypropylene diamine), both received from Resolution Performance Products LLC. They were mixed in stoichiometric proportions of 69 wt% EPON 862 and 31 wt% Epikure 3274. This resin system is commonly used for VARTM because of its low viscosity (approximately 0.1 Pa-sec) and ability to reach gelation at room temperature in about 6 hours.   The density of the cured resin was taken as 1.16 g/cm^3.

2.2 Process Details

The experimental details of the VARTM set-up is described in this section, as well as why each element was chosen. See Appendix for a detailed list of the various equipment and supplies used.

2.2.1. Molding Surface and Vacuum System: The molding surface was made from a 1.27 cm (0.5 in.) thick aluminum plate that was bolted to a steel cart. A 0.95 cm (0.375 in.) diameter hole was tapped through the surface near one edge and connected to a catch pot and vacuum pump located below the plate. The advantage of drawing vacuum through the molding surface was that it eliminated a tube from passing through the vacuum bag, which eased the vacuum bag set up and improved the quality of the seal (a key issue). The mold surface was treated with several coats of Frekote 700 NC prior to use. A 2-3 cm perimeter around the table was taped off during application of mold release, since this is where the vacuum bag sealant would be placed. After "releasing" the table, the tape was removed. When not in use, the table was covered up with polyethylene sheet plastic to keep it clean and scratch free. The catch pot included a vacuum gage. The purpose of the catch pot was to eliminate the possibility of resin accidentally flowing into the pump. The pump was connected to the catch pot through a quick-disconnect type of fitting. This allowed the catch pot and vacuum bag assembly to be easily disconnected from the vacuum pump during various times, for example during leak testing and resin degassing prior to infusion.

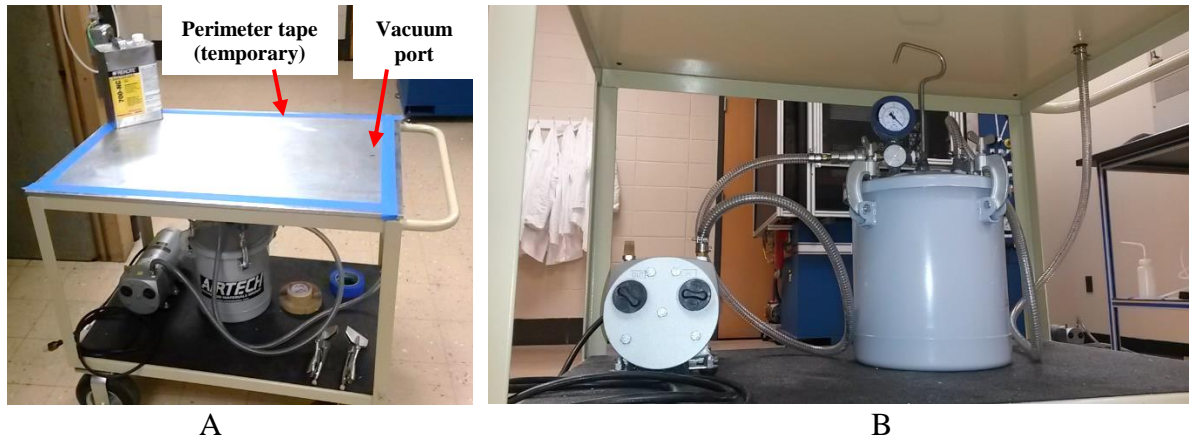A   B

Figure 1. A) VARTM table, shown here with perimeter taped off during application of mold release agent. B) Vacuum pump and catch pot, located under the table. Notice the vacuum line connects from the catch pot to a port that feeds through the bottom of the table.

2.2.2. Bagging Sequence

Given the limited table size, we usually molded only one or two panels at a time. Figure 2A illustrates a typical layout for a single panel, while Figure 2B shows an effective configuration for molding two panels simultaneously. The fabric stacks were placed on the table as shown. The blue tape on the edges of the fabric helped reduce fraying of the fiber tows during cutting. There was no reason to remove the tape because we normally trim the edges of the cured panels prior to testing.

Vacuum bag sealant was placed around the perimeter of the table, and the brown release paper was left on to protect it during the set-up process. A perimeter vacuum track was created by placing 2.5-5 cm (1-2 inch) wide strips of cotton breather just inside the vacuum bag sealant, including covering the vacuum port hole in the table. The purpose of this element was to distribute vacuum uniformly around the panel(s) in an attempt to draw resin evenly in all directions from a central feed port (to be placed in the center of the panel). For the dual panel set-up, a cotton strip was also placed between the two panels, surrounding each panel with a vacuum source on all four sides. The cotton breather material was chosen because we already had a supply of it in stock (normally used for autoclave curing), but alternative materials could be used such as fiberglass fabric. The breather material must not collapse during vacuum bagging, thereby keeping an open path around the panel(s) for the flow of air and a uniform level of vacuum. The pressure difference between the feed port (P_{abs} = 1 atm) and vacuum location (P_{abs} = 0.1 atm approximately) creates the driving force for resin flow and affects the thickness of the panel. This is why the perimeter vacuum channel was used rather than pulling vacuum from only one side.
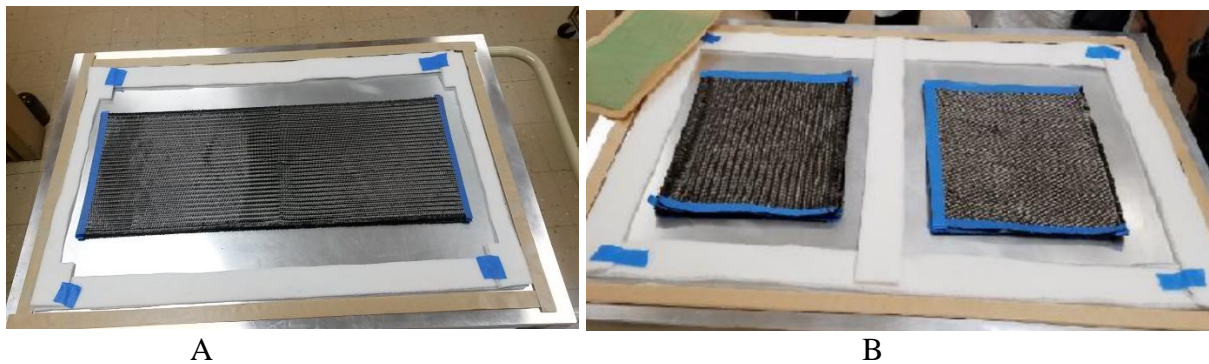

Figure 2. First step of bagging sequence: place fabric layers on table and surround by a perimeter breather track and vacuum bag sealant, A) single panel layout, B) dual panel layout.

Next, a continuous layer of porous peel-ply was placed over the panels, extending to the perimeter vacuum track (Figure 3). A peel ply is commonly used in VARTM processes to separate the panel from the resin distribution medium (described in the next paragraph), which is often placed above the panel and has to be moved after cure. Otherwise, the distribution medium would permanently adhere to the panel. The peel ply must be porous to alloy resin to seep through it.   Also, the peel ply serves as a flow path for air and liquid resin between the fabric stack and the perimeter vacuum channel.   Its permeability is much higher than the resin distribution medium, which slows down the resin once it reaches the edge of the panel. A few pieces of tape were used to hold the peel ply in place during subsequent operations.

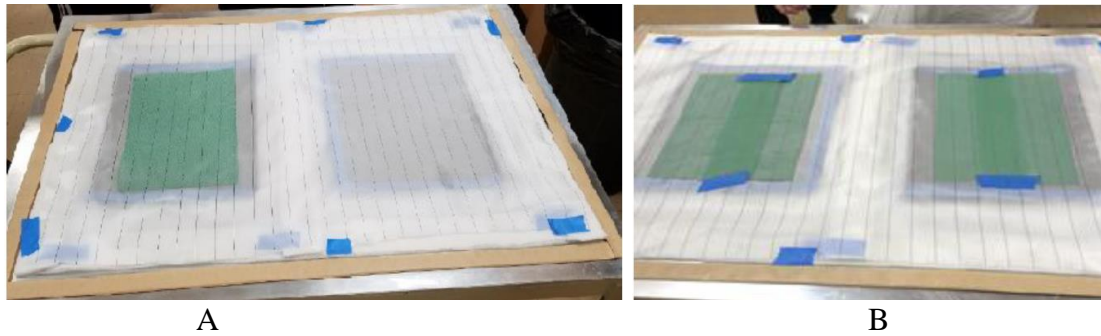<center>A   B</center>

Figure 3. A) placement of peel ply over stack and connecting with perimeter vacuum track. The black lines serve as markers since the white fabric usually becomes optically transparent after it fills with resin, and B) placement of resin distribution medium above peel ply.

The next step involved placing the resin distribution medium above each panel. Generally there are many possible variations in materials and geometries that will work. The medium is comprised of a low permeability material, usually resembling a screen or mesh, which doesn't collapse under the vacuum bag. The main purpose of the medium is to distribute the resin as it flows into the bag relatively quickly and uniformly to all parts of the panel (thus the need for high permeability material). Without the medium, all the resin would have to flow from a single feed location through the fabric stack toward the vacuum source. The fabric stack itself usually has a low permeability due to the presence of densely packed fibers. Therefore, it would not fill in a practical amount of time, or it may not fill at all given the limited pressure gradient which could not overcome the resistance to flow. The resin distribution medium solves this dilemma by allowing resin to flow quickly across the top of the panel, at which point is soaks vertically downward through the thickness. The medium is usually terminated within a few centimeters of the edge of the panel. The strategy is to flow resin quickly to near the edge, then slow it down to allow the resin to wet out the panel through the thickness. Also, if resin reaches the edge of the panel it will "race track" (flow quickly) around the edge of the panel toward the vacuum source since this is a lower resistance path. Race tracking could potentially cut off the vacuum from the panel, leaving it partially dry.

In our trials, we cut the green screen material into a rectangle with dimensions that left a 5-cm gap between its perimeter and the edge of the panel (see Figure 3B). In addition, we added a narrower strip (5 cm wide) of the screen material on top of that, in an attempt to quickly flow resin along the long axis of the panel to reach the far edge. One of the central challenges is that the resin will naturally flow in a radial pattern from the feed port to the vacuum perimeter, unless otherwise affected by the path of resistances. Ideally the resin would flow in a rectangular pattern and reach the four corners at the same time, but this is difficult to achieve in practice. Fortunately there is some robustness to this process such that full infusion can be achieved in a variety of ways.

The final step in the bagging sequence was to install the vacuum bag with resin feed system, see Figure 4. First a piece of vacuum bag slightly larger than the table was cut out and draped over the table. Then a metal screw-in connector (normally used for electrical junction boxes) and a 1.9 cm (0.75 inch) diameter metal washer were used to form the feed port. A hole was cut in the

bag, and the bag was sandwiched between the washer (below bag) and the flange on the screw-in connector (above bag). The screw-in connector extended through the bag and washer, and the nut was tightened below the washer by hand. The main reason for choosing these specific items was that they allowed the vacuum bag to sit as flatly as possible on the lay-up. This arrangement minimized wrinkles and pleats at the vacuum bag sealant, thereby *improving the quality of the vacuum seal.* An additional benefit was that these parts were relatively inexpensive and available at a local hardware store. The assembly was not sufficiently vacuum-tight, therefore vacuum bag sealant was placed around the metal port to improve the seal (Figure 5).

A feed port was placed at the center of each panel. The main reasons for this decision were 1) to allow the resin to flow as uniformly as possible across the entire area of the panel, and 2) minimize the variation in pressure from the feed port to the panel edge, which ultimately affects the panel thickness variation. The feed port was expected to create a defect in the center of the panel. However, given our goal of fabricating panels for mechanical testing, this issue was circumvented by discarding that area of the panel.

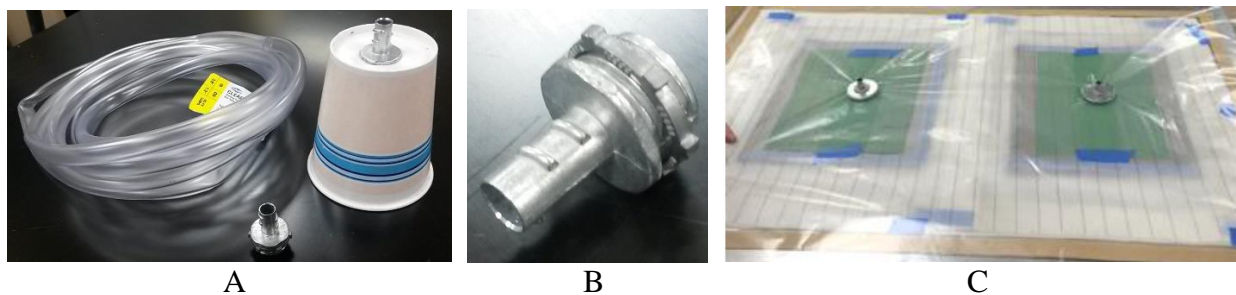A   B   C

Figure 4. Details of the resin feed system, A) individual components, B) close-up of the feed port, and C) vacuum bag with installed feed ports.

The feed port was connected to a feed cup using an inexpensive PVC tube. The assembled vacuum bag and feed system is shown in Figure 5. Prior to infusion and during leak testing, the tube was clamped off using a vice-grips. It was not necessary to use vacuum-rated hose for the feed tube, because once the resin flows the pressure in that region will be near atmospheric and therefore will not collapse during infusion. The feed cup was comprised of a paper cup with another metal screw-in connector inserted into the bottom. It helped to use 5-minute epoxy to seal the connector to the cup to prevent resin leakage during infusion. The reason for feeding from the bottom of the cup (rather than extending a tube over the top of the cup) was that it eliminated the possibility of trapped air in the feed tube. In earlier trials, trapped air was observed to be detrimental because it reduced the diameter of the feed tube. It is well established in fluid mechanics that the flow rate of liquid in a tube for a given pressure drop is proportional to the fourth power of the tube diameter for laminar flow. Therefore, trapped air in the feed tube can produce a significant resistance to flow (by reducing the effective diameter for flow) and possibly prevent complete filling of the panel prior to resin gelation.

The feed cup was elevated about 15 cm (6 inches) above the panel using a ring stand (Figure 5). The location of the feed cup actually has a two-fold effect on the process. Using a higher

elevation relative to the panel will allow the resin to flow more quickly due to the pressure head. However, the increased hydrostatic pressure of the fluid will increase the pressure at the feed port and reduce the vacuum level there. This leads to a thicker panel and looser bag. In our study, we kept the elevation constant, and the feed tube was kept as short as possible to reduce resistance to flow. Other potential strategies are to locate the cup lower than panel, start with a high elevation and lower it after the panel is mostly full, and use a larger diameter feed tube.
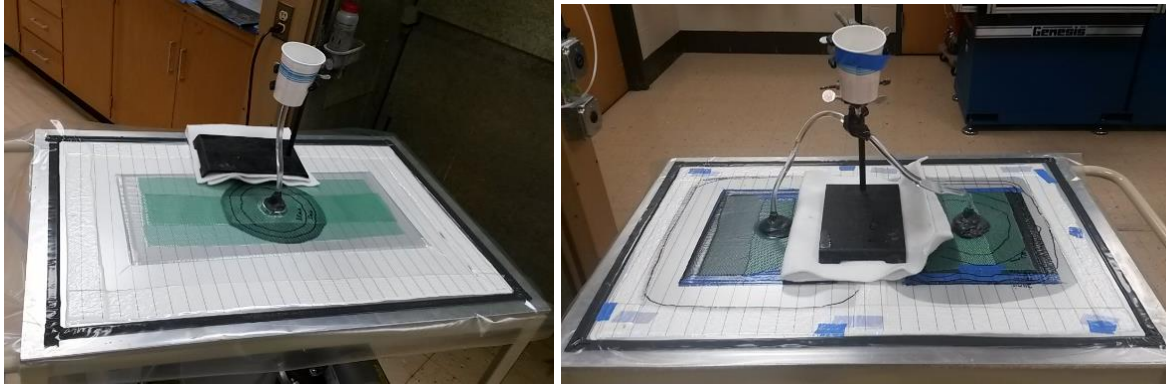

Figure 5. Assembled vacuum bag and feed system for single panel (left) and dual panel set up (right). These photos were taken after the infusion process begin.

2.2.3. Resin Preparation and Infusion

After the vacuum bag was assembled and clamp applied to the feed tube, the vacuum pump was turned on for at least 10 minutes. The vacuum gage was then checked to ensure the maximum achievable vacuum level was obtained, which was about 93 kPa of vacuum (27.5 in Hg or 0.92 atm of vacuum) for the given pump. Then a leak check was performed by disconnecting the pump from the catch pot. An acceptable leak rate was no more than 350 Pa (0.1 in Hg) over 15 minutes. During this time, we prepared the resin by weighing out and mixing the epoxy and curing agent. The total weight of resin was about 1.25 times the weight of the dry fabric. The resin was degassed at room temperature using a vacuum chamber (not shown here) for 10 minutes. After the leak check, the pump was reconnected to the catch pot, and the cup was filled with resin. The clamp was removed from the tube, and the infusion process was observed. We used a marker to draw lines on the bag to record the location of the flow front at various times, for example every 2-5 minutes.

Care was taken to avoid premature resin gelation in the cup by keeping the resin in two separate containers and refilling the feed cup only when it was almost empty. Having a large quantity of resin in one container can lead to an unwanted temperature rise due to the heat release from the resin as it slowly cures at room temperature. The resin is inherently a good thermal insulator, so it is easy to build up heat in the cup, which accelerates the cure reaction and can lead to resin gelation sooner than the resin that has infused into the bag. This will result in incomplete filling of the panel. Therefore, resin management is an issue even with a lab scale system.

After the panel was fully infused, the feed tube was clamped off, and the vacuum pump was disconnected from the catch pot. The strategy was to try to even out the pressure across the bag,

although the catch pot still served as vacuum reservoir. In any case, the pump could be turned off at that point. The panel was left in the bag to gel and harden overnight under vacuum. The next day, the bag was removed and infusion media peeled off. The panels were a little soft, so they were post cured in a free standing state in an oven at 100 °C in air for 1 hour. After that, the panels felt stiffer and had the characteristic carbon "ring" to them.

2.3 Testing Procedures

A wet saw with diamond blade was used to cut the panels into the various coupons needed for testing, as well as to remove the section immediately below the feed port (which was then discarded). Several small samples were cut from three locations and tested for density using ASTM D792 (water buoyancy). At least 2 more small samples were potted in epoxy resin, polished with a Buehler AutoMet 250, and examined with an optical microscope to view the cross section for porosity and fiber uniformity.

Tensile testing was conducted via ASTM D3039. The tensile coupons were cut from the panels using a diamond blade wet saw. The 5HS coupons were 25.4 cm long x 2.54 cm wide (10 in. x 1 in.), while the braided coupons were 25.4 cm long x 3.58 cm wide (10 in. x 1.41 in.). The braided coupon width was about 40% greater than specified in the standard (2.54 cm or 1.0 in) because of the discrete nature of the braided fabric architecture. A width of 3.58 cm (1.41 in.) allowed for four "unit cells" of the braid pattern to be captured across the width. Each tensile coupon was further processed by adding 5-cm long (2 in.) fiberglass tabs to each end, as well as a bonded strain gage to the middle of the coupon. The testing was conducted with an Instron model 5985 materials testing system, using wedge action grips and extension rate of 2.54 mm/min (0.1 in/min).

The uniformity of each panel's thickness was evaluated by using a digital calipers to measure the thickness of the four tensile coupons at three different locations each. An approximate map of these samples is given in Figure 6. The fiber volume fraction (V_f) was calculated from two methods. The first was based on the panel thickness measurements that were used to calculate the per-ply-thickness (PPT = total panel thickness / # of layers), see Equation 1. The second method used the composite density (ρ_c) results and the rule of mixtures, see Equation 2. The fiber density (ρ_f) was taken from Table 1, and the matrix density (ρ_m) was 1.16 g/cm^3.
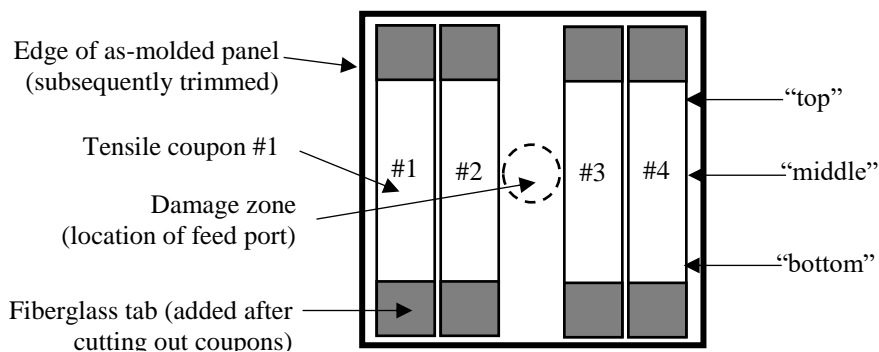

Figure 6. Approximate map of tensile coupons, showing where they were cut from and where thickness measurement were made (top, middle, bottom) for each coupon.

$$V_f = FAW / (\rho_f \times PPT) \tag{1}$$

$$V_f = (\rho_c - \rho_m) / (\rho_f - \rho_m) \tag{2}$$

3. RESULTS

3.1 Process

Photos of a single panel during infusion are given in Figure 7, while a photo of two panels that were simultaneously infused is given in Figure 8. Generally the resin flowed quickly through the green resin infusion media, and then slowed down significantly after that. The strategy of terminating the resin infusion media several centimeters before the edge of the panel was successful. The initial circular flow front is evident in Figure 7 (left), but then it assumed a more rectangular pattern after the resin reached the edge of the green infusion media. The actual dimensions and shape of the media could be further optimized to better produce a situation where the resin reaches the perimeter of the panel at the same time. However, overall the resin flowed in a reasonable manner and no problems were encountered.
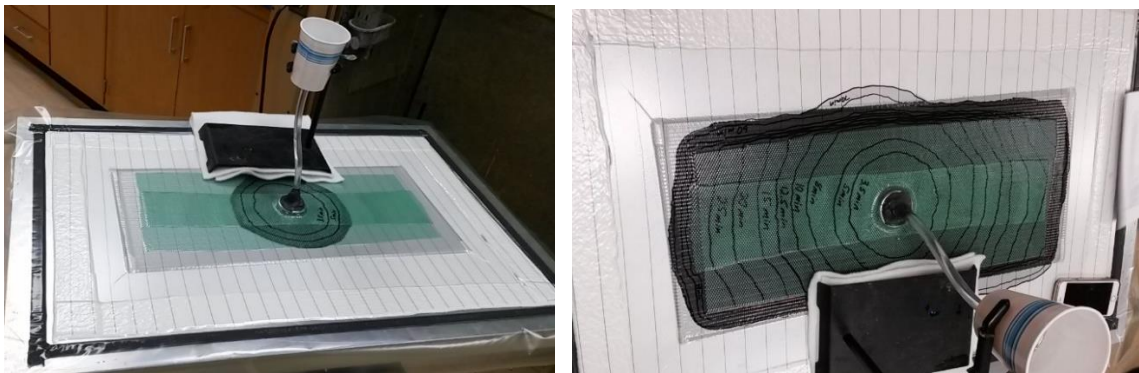

Figure 7. Single panel during infusion (braided fabric panel). (Left) 7 minutes after infusion began, (Right) 70 minutes after infusion began.
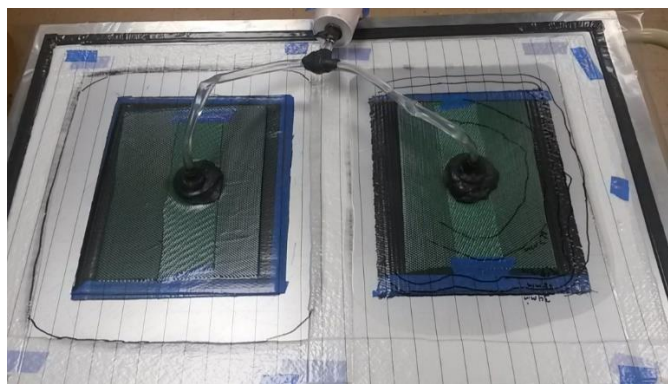

Figure 8. Two panels simultaneously that were simultaneously infused, each through its own feed port and tube (left) 5HS panel, and (right) braided fabric panel. This photo was taken after infusion was complete.

One of the surprising results was that the 5HS panel infused in about 10 minutes, while the braided fiber panel of similar dimensions required approximately 35 minutes (Figure 8). This difference is due to the permeability of the fabrics. The feed tube to the 5HS panel was clamped off after 20 minutes to reduce the possibility of resin flowing into the perimeter vacuum track. The large single panel made from braided fabric (Figure 7) required twice as long to infuse (70 minutes) compared to the smaller one (Figure 6, right). This demonstrates a key issue with scaling to larger sizes: the velocity of the resin flow front continually decreases over time. This is due to the reduced driving force, which is the pressure drop between the resin flow front and the vacuum. At the beginning of the infusion, the resin entering the bag is near or at atmospheric pressure. As the resin flows outward into the composite, the pressure at the flow front gradually drops and the area to fill increases. At some point, the difference in pressure between the flow front and the vacuum will not be high enough to overcome the resistance to flow. This is analogous to flow of liquid in a horizontal pipe, where a given pressure drop will only be able to drive the fluid a finite distance, which depends on pipe diameter and fluid viscosity. In industrial practice of VARTM, this problem is solved by using multiple feed lines placed at regular intervals. For our small-scale VARTM process, one feed tube proved to be sufficient for the materials infused so far.

A photo of the panels after unbagging, post cure, and trimming is given in Figure 9. The circular defect caused by the feed port is visually evident. The dimensions of the defect were approximately 5-7.5 cm (2-3 inches) in diameter. The bottoms of the panels (not shown here) were almost entirely infused. There were no dry fibers, but there were a few small locations where some voids were evident (<2% of the area).

Feed port defect about 5-7.5 cm diameter
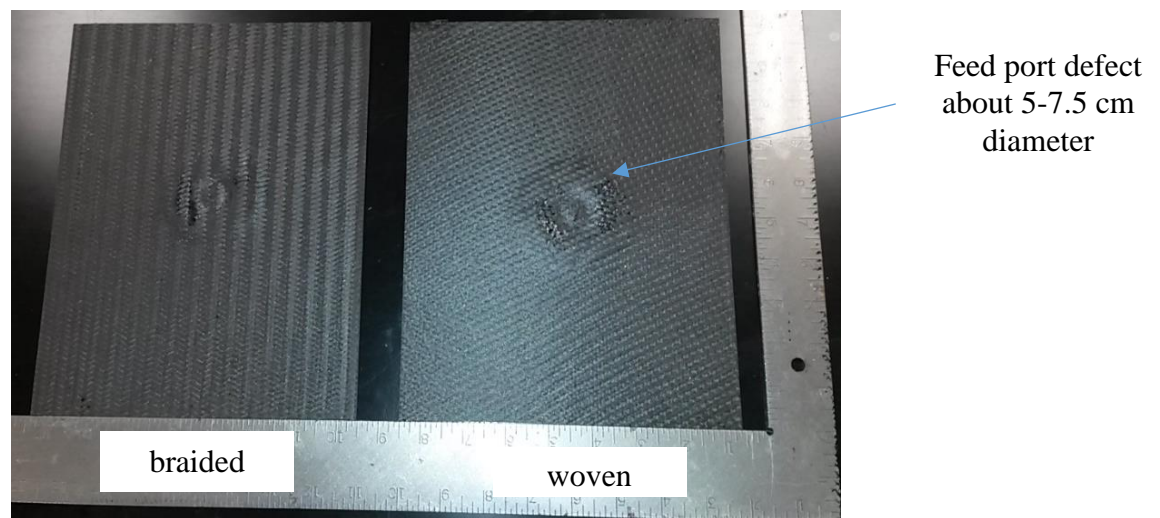
braided

woven

Figure 9. Photo of panels (top side) after post cure and trimming the edges. The panel dimensions were approximately 25 cm long x 20 cm wide (10 in. x 8 in.)

3.2 Physical Properties and Photomicrographs

The thickness measurement results are given in Table 2. The variation in thickness for the 5HS panel was relatively low, and the calculated value of V_f (0.54) was reasonably high for a VARTM process. The braided panel had a larger variation in thickness, although that was expected due to the "lumpy" nature of the fabric which produces "hills and valleys" from the braided tows. Accordingly, these thickness values correspond mostly to the "hills" since they were measured with a calipers that contacted the highest points on the panel. Subsequent photomicroscopy analysis indicated the average thickness of the braided panel was about 7 % less than the calipers results. Therefore, the calculated fiber volume fraction given in Table 2 for the braided panel (0.494) slightly underestimates the true value.

Table 2. Thickness measurement results for tensile coupons, and average fiber volume fraction result. See Figure 6 for location of top, middle, bottom.

	Thickness of 5HS fabric coupons (mm)				Thickness of braided fabric coupons (mm)			
	#1	#2	#3	#4	#1	#2	#3	#4
Top	2.00	1.96	1.95	1.97	2.24	2.16	2.23	2.34
Middle	1.97	1.94	NA[1]	1.94	2.18	NA[1]	NA[1]	2.24
Bottom	1.95	1.94	1.98	1.97	2.17	2.16	2.22	2.23
Mean (mm)	1.96				2.22			
C.O.V.[2]	0.9 %				2.5 %			
PPT^3 (mm)	0.392				0.444			
$V_f{}^4$ (unitless)	0.541				0.494			

[1] NA: not available – this part of the coupon was significantly thicker due to its location near the feed port. Its value was not included in the average.
[2] C.O.V. = standard deviation / mean
[3] PPT = mean thickness of panel / 5 (where 5 is the number of layers)
[4] V_f calculated from Equation 1

The density results and corresponding V_f results are given in Table 3. The value of V_f calculated from this method for the 5HS panel is in excellent agreement with Table 2 (0.542 vs. 0.541). The result for the braided fiber panel was slightly higher than that in Table 2 (0.519 vs. 0.494), although that was expected since the value in Table 2 was underestimated for reasons discussed in the previous paragraph. In comparison, the braided fiber panel was slightly less dense than the 5HS panel, which was expected due to the nature of the fiber architecture as discussed earlier. Overall, the resulting V_f range for both panels (about 52-54 %) was considered to be reasonable for VARTM processing, and certainly good enough to conduct mechanical testing. The importance of calculating an accurate value of V_f is linked to its use in normalizing mechanical property results. For example, tensile strength and modulus are often normalized to an equivalent

panel with 60% fiber volume fraction. This is usually done to make better comparisons between composite material systems.

Table 3: density results and average fiber volume fraction

Panel	Specimen #	ρ_c (g/cm^3)	V_f^1
5HS	1	1.504	
	2	1.495	0.542
	3	1.505	
	mean	**1.501**	
Braided	1	1.495	
	2	1.506	0.519
	3	1.491	
	mean	**1.497**	

[1] V_f calculated from Equation 2 using the mean density result.

Photomicrographs of the panels are given in Figures 10-11. Overall there was little or no porosity in either panel. However, there were resin rich areas. Some of these are normal, since there are periodic "open" spaces in fabric preforms where tows cross each other. However, in a few random locations, we observed resin rich areas between plies, for example Figure 10B. We are not certain whether this was caused by incomplete nesting of the plies during layup, or from variations in how the resin flowed through the panel during infusion. Also, in some cases, the fiber packing within fiber tows was not uniform (Figure 11). Again, we are not certain whether this was caused by variation in the original preform or a process-induced effect. Nevertheless, the overall quality of the microstructure was good.
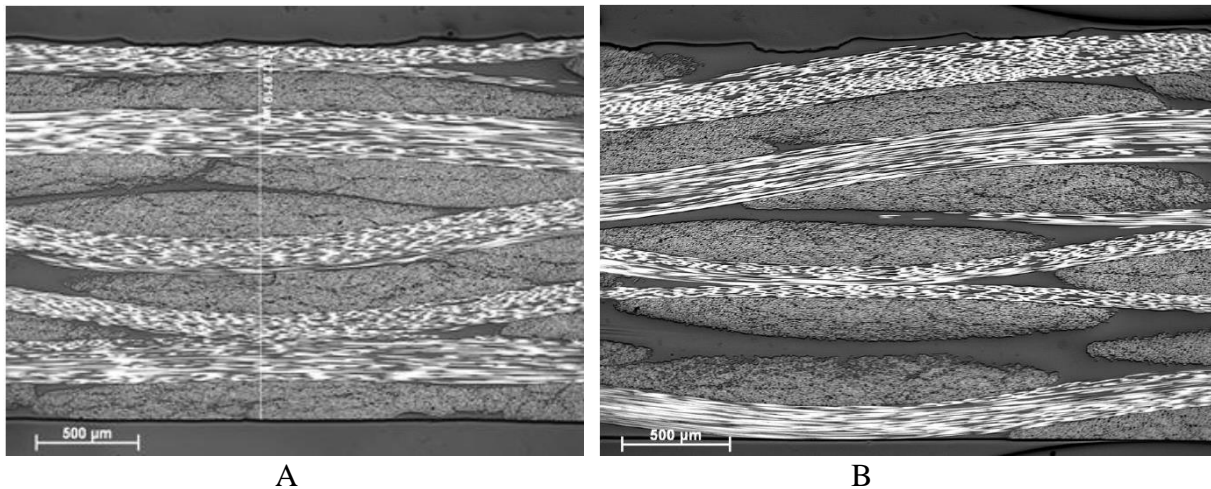

A   B

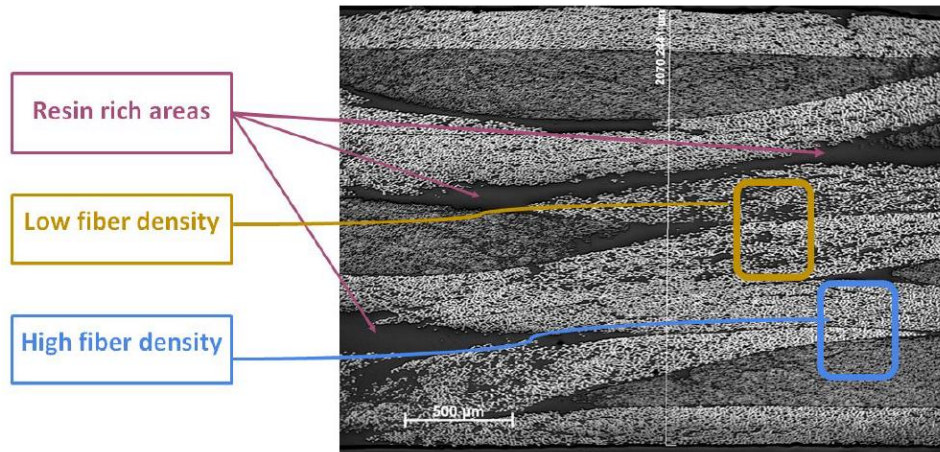Figure 10. Photomicrographs of polished cross section of 5HS panel.

Figure 11. Photomicrograph of polished cross section of braided panel.

3.3 Mechanical Properties

The tensile testing results are given in Table 4. These results are reasonable for the given materials. For example, the modulus of the 5HS panel was very close to that predicted by the rule of mixtures for a fabric with 50% of the fibers in the tensile direction (i.e. 0°/90° fabric), a fiber volume fraction of 60%, and fiber modulus of 234 GPa (34 MSI), where $E_{predict}$= 234 x 0.6 x 0.5 = 70 GPa. The modulus of the braided panel was about 25% lower than 5HS because only 33% of the fibers were aligned in the tensile direction, with some contribution from the ±60° fibers. The modulus of the braided panel was comparable to that obtained in other studies using this material when adjusted for fiber volume fraction [8]. The strength of the braided panel was only about 12% lower than 5HS, and its failure strain was slightly higher. Overall, these results indicate that the panels were of good quality, but further study would be required to better characterize the mechanical behavior and failure mechanisms. For the purpose of the current study, the results simply verify that the VARTM process worked reasonably well.

Table 4: tensile results.

Panel	Specimen #	Tensile strength[1], MPa (ksi)	Tensile modulus[1], GPa (Msi)	Failure strain (%)
5HS	1	956 (139)	72.5 (10.5)	1.32
	2	905 (131)	73.2 (10.6)	1.20
	3	1000 (145)	72.0 (10.4)	1.38
	mean	**954 (138)**	**72.6 (10.5)**	**1.30**
Braided[2]	1	858 (124)	53.3 (7.73)	1.55
	2	801 (116)	52.0 (7.54)	1.54
	3	887 (128)	55.4 (8.04)	1.63
	mean	**849 (123)**	**53.6 (7.77)**	**1.57**

[1] normalized to a fiber volume fraction of 60%

[2] "longitudinal" coupons (the 0° fiber tows were oriented parallel to the direction of tensile stress)

4. CONCLUSIONS

A simple lab-scale VARTM process has been developed and demonstrated for making flat composite panels. Although the process is not ground-breaking in its novelty, the contribution of the work was to thoroughly document and explain the process for others to implement and quickly come "up to speed" when trying to evaluate new materials for VARTM processing. The process is easy to set up and is adequate for making flat panels of approximately 30 cm x 45 cm (1 ft. x 1.5 ft). This size will provide ample material for a wide range of mechanical and physical tests. The uniformity of the panels produced were good as indicated by thickness and density measurements. Photomicrographs and tensile testing results further validated the reasonable quality of the panels.

5. REFERENCES

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6. APPENDIX

LIST OF VARTM FITTINGS AND SUPPLIES

- Aluminum plate: MIC-6® aluminum cast plate, 93.3 cm x 62.9 cm. x 1.27 cm (36.75 in. x 24.75 in. x 0.5 in.)

- Cart: steel instrument cart, 93.3 cm x 62.9 cm. (36.75 in. x 24.75 in.) with 20 cm (8 in.) diameter pneumatic wheels (ULINE)

- Pump: Gast ¼ HP oil-less rotary vane vacuum pump (Grainger item #4F740)

- Catch pot: RB451 Vacuum Reservoir, 2.5 gallon tank (Coast-Line International)

- Vacuum Tubing (below table): vinyl tube with internal steel coil, OD 1.59 cm (0.625 in.)

- Quick disconnect fittings: AQD 500TF (AirTech International / Coast-Line International)

- Vice grips: Locking sheet metal clamp (AirTech International / Coast-Line International)

- Vacuum bag – Wrightlon 6400 bagging film (AirTech International / Coast-Line International)

- Vacuum bag sealant: SM5127 (black) Tacky Tape (Northern Composites)

- Cotton breather: Airweave N-10 (AirTech International / Coast-Line International)

- Peel ply: Econostitch G polyester peel ply with black tracers (AirTech International / Coast-Line International)

- Resin infusion media: Greenflow 75 (AirTech International / Coast-Line International)

- Resin feed tube: EZ-FLO clear vinyl tubing, ID 0.95 cm (3/8 in.), OD 1.27 cm (1/2 in.) (Lowe's item #98566)

- Feed port: Pro Connex Screw In Connector, 0.95 cm (3/8 in) trade size, 1.27 cm (0.5 in.) knockout (Lowe's item #42009)

- Paper cup: Uline signature paper cold cups, 355 mL (12 oz) (ULINE item # S-20155)

- Degas chamber: 3 gallon aluminum vacuum chamber (Best Value Vacs)