

THE USE OF FLOW SIMULATIONS OF LARGE COMPLEX COMPOSITE COMPONENTS USING THE VARTM PROCESS

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SUMMARY: The Vacuum Assisted Resin Transfer Molding process has gained popularity due to the affordable parts that have been made, now approaching complexity and quality found in traditional aerospace processes. However, the progression of the resin through the mold is complex and was historically not well understood. Therefore, traditionally a trial and error approach was used based on a foundation of tribal knowledge to produce composite parts of good quality. For this reason, during the past decade, significant academic research has been applied to advance processing techniques for composite materials manufacturing. One main research thrust has been the simulation of the resin progression through the fibrous preform. This approach enables understanding of how the resin flows through the mold, and reduces the trial and error approach to infusion design. This tool enables to optimize the processing parameters, as well as weight the benefit of alternative approaches. In this study, a flow simulation tool is used to facilitate the design of the infusion strategy. The effect of the location of the infusion runner channels is explored, with optimal location and pathways proposed. Further, the timing of resin arrival into the various ports of the mold is studied. In order to add repeatability to the process and reduce the chance for error, robustness was used as one of the criteria in selection of the infusion strategy in contrast to the standard approach of resin bleeding and recycling. All of these studies culminate in ensuring a robust infusion approach, both minimizing scrap and maximizing processing efficiency. This will further the aim of manufacturing composite parts with the VARTM process with properties equivalent to autoclave quality.

INTRODUCTION

Previous work described the desire to move from a legacy design for a helicopter component to one using of unitized carbon reinforced composite structure [1]. The baseline structures typical in legacy rotorcraft platforms consist of sheet metal built up with fasteners, combined with secondarily fastened skins of aluminum or composite. The high part count, including numerous fasteners, contributed to the high acquisition cost of the baseline structures. Also, due to physical abuse of these thin skinned structures in the field during maintenance operations, support costs were high due to their and their lack of durability and need for repairs.

Redesign of the built-up legacy structure considered replacement metal stiffening elements with integral composite stiffeners that could be co-infused and co-cured as a single part, thereby eliminating the high part count, including numerous fasteners. Given the baseline design considerations and process capability of Vacuum Assisted Resin Transfer Molding (VARTM), core materials were not deemed optimal for this application. Although core provides a low-cost and lightweight solution, the sandwich construction presents issues related to quality assurance, reparability, and systems and interface attachment. Honeycomb core would require a separate carving and forming/sealing operation for the resin infusion, while foams present their own challenges with moisture absorption and parasitic resin infiltration that can add significant weight over large wetted surface areas.

As an alternative to sandwich stiffened skins, discrete monolithic laminate stiffeners were considered for skin reinforcement. This approach was expected to significantly reduce cycle time and cost by integrating individual substructure element and skin fabrication and assembly into one single operation. Blade stiffeners were arranged in rectangular cellular elements, or modular bays, over a solid laminate of constant thickness. In the interest of minimizing weight while increasing skin stiffness and durability of the structures, carbon fiber reinforcement was considered for the skins and stiffeners where glass fabrics materials were employed originally in the legacy designs. The resulting design possessed greater rigidity and potential for reduced support costs due to less damage during operations and maintenance, without exceeding the baseline weight.

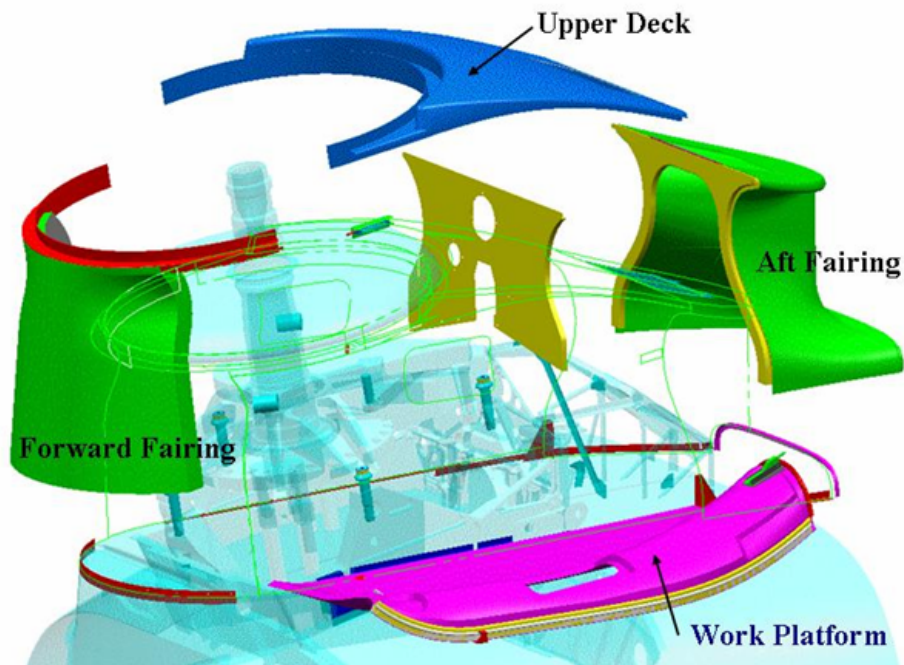


Fig. 1 Upper deck demonstration component as part of a representative pylon shroud from a rotorcraft platform.

This integrally stiffened structural design concept was used to demonstrate the producibility, performance, and affordability of the design and manufacturing process for rotorcraft structures

using the HypPerVARTM™ and the Affordable Feature Integration (AFI) approach [3]. The demonstration skin structure was selected and sized from an upper deck component of a representative pylon shroud from a rotorcraft platform. The relationship of the size and complexity of interface fit-up of this upper deck component to other elements of the pylon shroud is shown in Fig. 1.

FLOW SIMULATION

To gain a better understanding of the filling stage of the VARTM process, a mathematical model and a computer simulation [4, 5] can allow one to “visualize” inside a closed mold. This approach can predict the flow behavior and therefore help to intelligently decide on the choice of the gate and vent placement for successful filling. With this goal in mind, Liquid Injection Molding Simulation (LIMS) [6, 7] was developed at the University of Delaware. This mold filling simulation program is based on the physics of flow through anisotropic porous media. The governing equations are solved numerically using a finite element / control volume approach. A fast solver in this program relies on incremental creation and inversion of the system matrix rather than repetitive matrix assembly and consecutive inversion [8]. In order to use this simulation tool, first a mesh must be generated. As LIMS has no inherent meshing capabilities, ABAQUS was used to generate the mesh. The solid model of the upper deck that was used to construct the mesh is shown in Fig. 2.

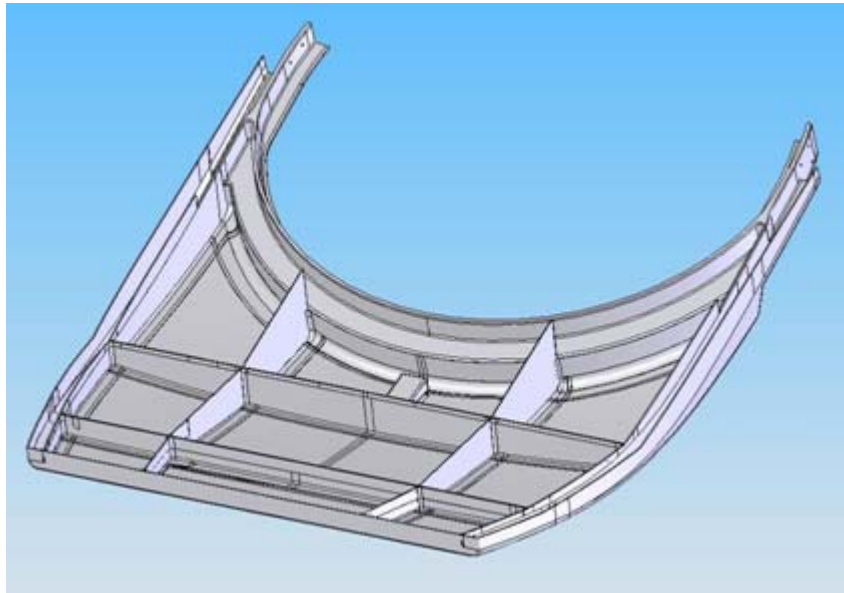


Fig. 2 The solid model of the upper deck.

From the solid model, a mesh was generated. Fig. 3a shows the resultant mesh, utilizing linear triangular elements to connect 10,703 nodes. After the initial mesh was generated, the resin runners used in the HypPerVARTM™ process were added. As LIMS allows for the combination of 1-D, 2-D and 3-D elements in the same mesh, 1-D elements were added along the resin runners to represent the resin flow channels. Fig. 3b shows the 1-D runners in yellow. The

permeability of these runners, which was higher than that of the bulk fabric, was applied by using the equivalent permeability for flow through a duct.

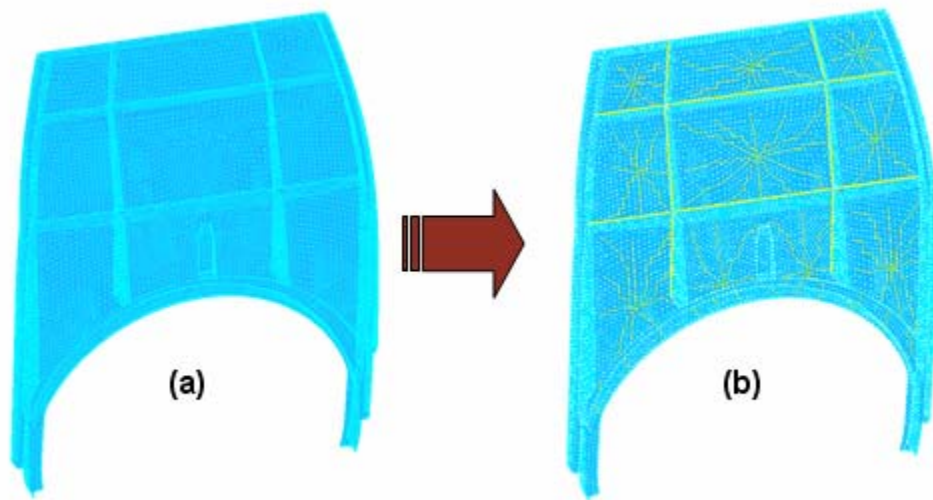


Fig. 3 (a) The original mesh and (b) the mesh with the runners added.

With the mesh preparation complete, the simulation was initiated. The resin injection gates were applied as boundary conditions at 10 location used during the infusion. The results of the flow simulation are shown in Fig. 4. The resin initially fills the 1-D elements representing the flow channels, and then begins to saturate the neighboring skins of the part, radiating outward from the center point (Fig. 4a). Then, the resin progresses and flow up the ribs (Fig. 4b). Finally, the resin flows down the lower legs of the part (Fig. 4c) and the infusion is complete. This resin infusion progression is very favorable for complete saturation of the part, as the main ribs and skins are well infused, and then final resin is pulled down along the lower legs, towards the ultimate vents.

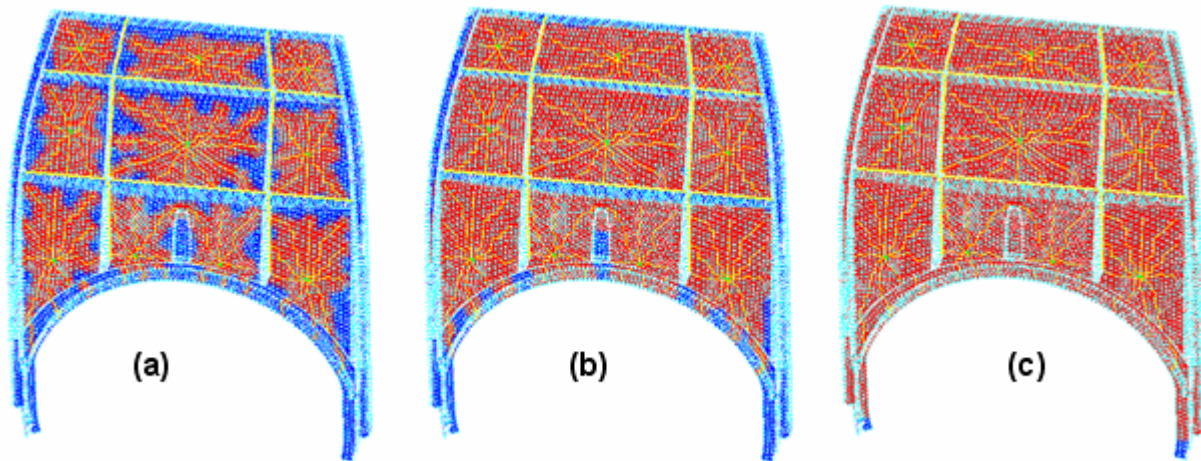


Fig. 4 The results of the simulation. Red indicates resin domain and blue is unfilled domain.

PROCESS MONITORING

Flow simulation can aid greatly in designing the infusion strategy to ensure a complete saturation of the preform, thus resulting in a properly manufactured composite component with consistent quality. However, it does nothing to ensure that the infusion progresses as simulated. Uncertainty in permeability as well as flow disturbances may lead to flow that progresses in a manner different than predicted. If plies are located slightly askew, or if some flow restriction exists, it will hamper or alter the infusion. For this reason, it is beneficial to have process monitoring in place for the infusion. While there are several approaches to process monitoring both externally outside of the mold or internally within the part, in this study an external resin mass flow metering system was used. To create this, two computer connected digital scales were used, one each for the infusion and vent buckets. By observing the time rate change of the mass of resin in the infusion bucket, the flow rate into the mold can be calculated. This allows the user to monitor the quantity of resin flowing into the mold at all time during the process. By doing the same with the vent bucket, the resin flow out of the mold (due to resin bleeding) can be monitored as well. By analyzing the difference between the infusion bucket and vent bucket, the mass flow, or flux, of resin into the mold can be accurately determined. By monitoring the flow rate into the mold versus time, the flow progression can be analyzed. This data can be compared to the simulation predicted data to ensure the infusion is progressing as expected. If resin appears to be flowing too slowly, sources of blockage can be found and remedied prior to any adverse effects. Further, when process monitoring is utilized in a production environment, part to part variation can be studied, and used for quality assurance in the manufacturing process.

MANUFACTURING OF UPPER DECK

The upper deck was manufactured using the HypPerVARTM™ and AFI approach [3]. This variant to the standard VARTM process uses standard VARTM molding approaches and materials, but replaces the traditional distribution media with a series of resin runners in the mold for resin delivery to the part. First, the mold is prepared, and release coat is applied for easy unmolding. Then, the initial skin plies are placed into the mold. Aluminum details which form and define the ribs are first wrapped with fabric and placed into the mold.

After the final plies are placed, the mold is covered with breather material to aid in distribution of the vacuum. The plumbing to introduce the resin in to the mold is placed (Fig. 5a). Then the mold is covered with a vacuum bag, vacuum is pulled, and the mold is placed into an oven, to prepare for infusion (Fig. 5b).



Fig. 5 (a) The bleeder material is placed and (b) the mold is bagged and placed into the oven.

After the mold has reached sufficient temperature, the resin is infused into the part. Once resin emanates from the mold through the vent tubing, the injection and vent lines are closed after sufficient bleeding. The part is then cured, demolded, and deflashed. The final part is shown in front and back views in Fig. 6, showing excellent surface finish and stiffener definition.

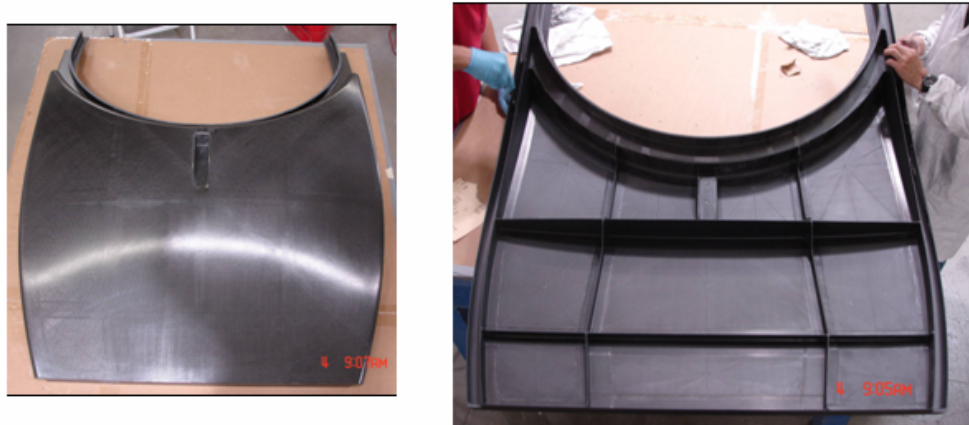


Fig. 6 The front and back sides of the final part.

PROCESS DATA ANALYSIS

With the simulation complete and the infusion of the actual part finished, the actual mold filling data could be compared against the model to ensure accurate results. The scale data was collected, and filtered to remove noise and to account for the vent bucket emptying. Then, the experimental and simulated results were compared. The results, as shown in Fig. 7, show that predicted and measured values compare favorably. The simulation does not take into account resin bleeding, so that portion of the infusion (past the star indicated by the graph in Fig. 7) is not comparable. There is some deviation that exists between the simulated and experimental results. This difference is mainly due to estimations made for the permeability for the resin absorbent materials, as well as simplifications in the part geometry modeling. Additionally, the waviness in

the experimental data near the end is due to the need for repeated emptying of the resin bleeding catch bucket. However, the overall trend is accurate, and the results compare well.

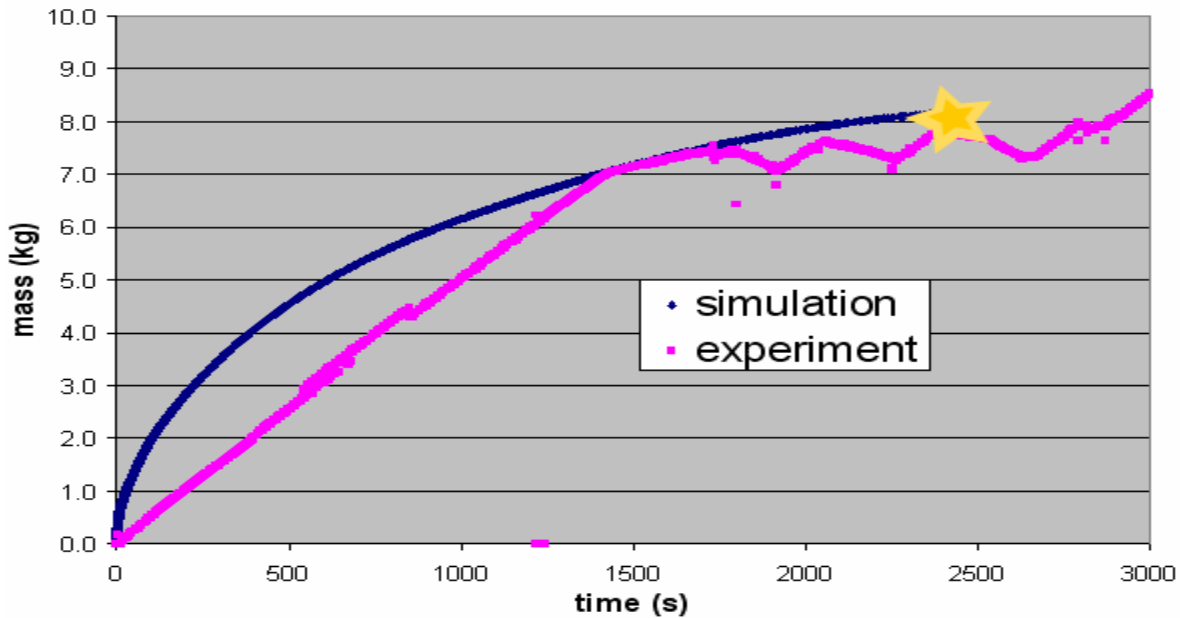


Fig. 7 The comparison of the resin intake into the part compared between simulation and experimental results.

SUMMARY / CONCLUSIONS

In this study, an example real-world part was selected to demonstrate some concepts of resin infusion simulation and process monitoring for advanced manufacturing of composite components. A new unitized design upper deck of a helicopter pylon assembly was selected, due to its complex shape. A flow simulation program was used to predict the resin infusion through the preform. Additionally, a process monitoring approach was designed and implemented in order to track the resin progression through the mold during infusion. Next, the part was made in the manufacturing environment. Simulated and experimental results compared favorably. This study demonstrates that advanced manufacturing techniques, such as VARTM of unitized structures, are sufficiently mature to be implemented into current manufacturing practices. The data collected could be invaluable in ensuring proper infusion, as well as providing quality assurance in a production environment. As confidence builds, further data collection could supplement what was utilized in this study, and the full potential for flow simulation could be realized for flow prediction through guidance of intelligent process monitoring.

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