

THE PROGRAMMABLE POWDERED PREFORM PROCESS FOR AEROSPACE: AFFORDABLE PERFORMANCE THROUGH COMPOSITES

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ABSTRACT

Developing more affordable fiber-reinforced composite structures is vital to many aerospace vehicles. Automated chopped fiber preforming technology offers the potential to dramatically reduce the cost of composite components and can be coupled with many affordable resin infusion methods. To this end, the Air Force Research Laboratory sponsored a program entitled “P4 for Aerospace (P4A)” to assess the feasibility of adapting the discontinuous fiber preforming technology identified as “P4” (Programmable Powdered Preform Process) to significantly lower the costs associated with aerospace composite material structures. Utilizing aerospace carbon fibers and epoxy resins, preliminary P4A properties were generated, structural complexities representative of aerospace requirements were investigated, and selected full-scale aerospace structures fabricated with P4A. A cross-company cost model was developed and validated during the program. Culmination of the P4A program demonstrated the technical feasibility of chopped fiber preforming as an aerospace process that can dramatically reduce the cost of properly selected composite structures.

KEY WORDS: Carbon Fibers, Preforms, Composites, Affordability

1. INTRODUCTION

Composites have demonstrated many attributes that translate into significant system-level benefits such as increased range, decreased fuel consumption, increased payload, lower life cycle cost, and innovative and enabling designs. Historically, the use of composites has been driven by performance improvements. Over the last decade, however, the aerospace industry has been driven by affordability as well— many government- and industry-funded programs have targeted the goal of reducing the cost of composites— affordable performance is the current challenge to composite materials and processes. However, most of these programs have taken conventional aerospace materials and processes and attempted to drive the cost down while maintaining the performance. While there have been many exciting developments, the direction of taking high performance materials and processes and trying to reduce their cost may not be the only route to affordable performance. One unique approach is to start with materials and processes that are cost driven and try to improve their performance. It is this approach that the Programmable Powdered Preform Process for Aerospace (P4A) program has taken, and it has looked to the historically cost-driven automotive industry for inspiration.

The automotive industry has historically been driven by cost, as cost is one of the main concerns of consumers. However, under current initiatives to develop technologies that achieve an 80-mile per gallon equivalent vehicle, improving performance has become a focus. A critical step to achieving a high fuel economy vehicle is the development of technologies to significantly reduce the curb weight of the vehicle, and composite materials are a leading approach. However, the cost of composites is a major impediment. The Automotive Composites Consortium (ACC) of the Partnership for the Next Generation Vehicle, sponsored by the Department of Energy in concert with General Motors, Ford Motor Company, and Daimler Chrysler, is addressing part of this challenge through their Focal Project II effort in which an S-10/Ranger/Ram-sized pickup truck box is the structural demonstrator of affordable composite technology. The ACC's performance goals were cost equivalency with the steel pickup box and its liner, a 30% weight reduction, and a rate goal that would result in a production rate of 80,000 units per year. The process that they identified for this project is the P4 method.^{1[1]}

^{1[1]} GM recently announced production availability on the 2001 Silverado of a chopped fiber preformed pickup truck box.

2. THE P4 METHOD

2.1 P4 Background The P4 technology is based upon the pioneering work conducted by Owens Corning Fiberglas, Battice, Belgium, and Aplicator System AB, Molnlycke, Sweden. Even though developed with internal funds, Owens Corning made the technology available free of charge, and Aplicator manufactured and integrated P4 at the National Composites Center (NCC). NCC was chosen due to the availability of space and the commitment of the State of Ohio to install a 1000-ton Structural Reaction Injection Molding (SRIM) press at NCC to be used for rapid infusion of the preforms to demonstrate production processing methods. P4 is a fully automated process for chopping and spraying fiberglass to produce a preform. The process consists of four major steps as shown in Figure 1.

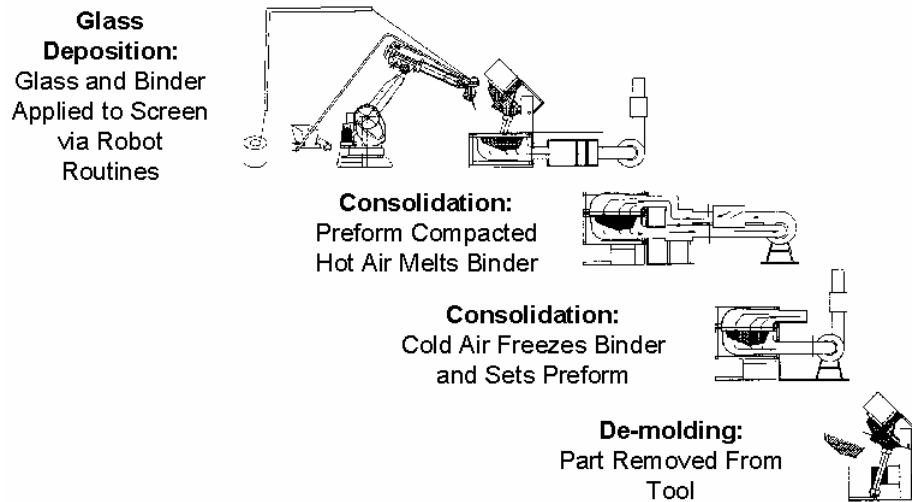


Figure 1. P4 Method Steps

The first step is to chop the fiber and spray it via a robotic arm onto the screen through which a vacuum is being drawn. At the same time, a powdered binder is also applied, usually 3 to 5 wt %. The next step is the consolidation of the preform by the passage of heated air through the preform; this sets the binder and holds the compacted preform in position. The preformed fibers and binder are then cooled by passing room temperature air through the preform. Once the preform is cooled, it is capable of holding its shape with careful handling and is simply removed from the tool and available for resin infusion.

The compelling attributes of the process include its automation, which provides for the rapid fabrication of preforms with very low “touch labor.” It offers the potential for reduced assembly through the ability to form complex geometries and net shapes. Fiber alignment is possible, and additional design flexibility may result from the process’ ability to change chopped fiber length and/or orientation “on the fly.” Rib stiffeners, openings, cores, and other elements may be integrated into the preform during its manufacture. All of this is possible while retaining very low material waste factors.

These attributes were major factors in the ACC's selection of this method for low cost, high performance preforms.

2.2 The P4A Program The P4A program is funded and managed by the Air Force Research Laboratory, Materials and Manufacturing Directorate. NCC is the prime and leads a team consisting of Boeing-Seattle, Boeing-St. Louis (formerly McDonnell Douglas), Lockheed Martin Aeronautical Systems, Northrop Grumman, and the University of Dayton Research Institute. The objective of the P4A program is the development and demonstration of low cost, rapid processing methods for aerospace composite structures. The approach is the assessment of the P4 technology for aerospace applications. The success metrics were defined as demonstrating that the P4 method adapted to aerospace-grade carbon fibers and resins could meet target property goals, that the process could fabricate structural complexities representative of aerospace requirements, that compelling cost savings could be demonstrated over conventional processes, and that the process could be enabling so that it could buy its way onto applications (Figure 2). The success

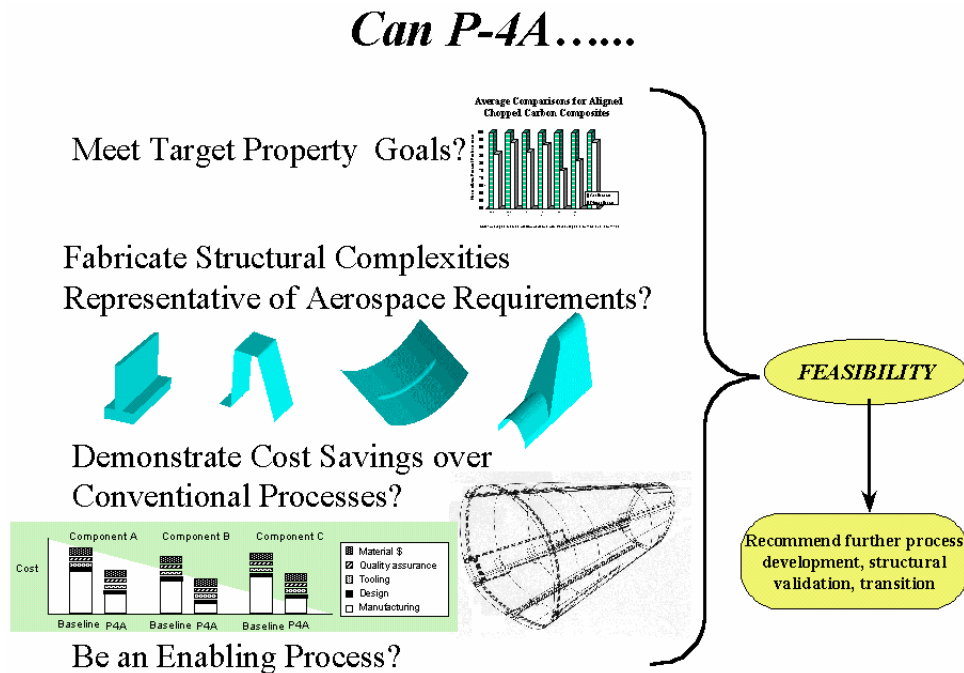


Figure 2. P4A Goals.

metrics were defined as critical; if met, then further development of the process, structural validation, and transition to development of actual flight hardware would be recommended.

Another objective of the program was to incorporate ACC's approach towards pre-competitive research and development. To do so, a team of all of the major airframers was formed, and all shared equally in the development of the technology in a very open and cooperative manner.

The effort was condensed into approximately one year due to delays in equipment availability. During that time, the existing P4 method was adapted to carbon fibers. The first carbon fiber preforms were fabricated, aerospace components were ranked, a shared cost model was developed, and a demonstration part was selected to both demonstrate the process and to validate the cost model. Details of the critical metrics are provided below.

3. RESULTS AND DISCUSSION

3.1 Material Properties Extensive literature searches of numerous discontinuous fiber forms indicated that 80% of the strength and greater than 90% of the stiffness associated with continuous fiber composites were attainable in discontinuous carbon fiber products. These values were initially adopted as target goals for the P4A program. However, during the course of a more intensive data review, which included articles from both the US and abroad as well as data packages from P4A team members, it was discovered that a very limited amount of available data dealt with aligned, discontinuous carbon fiber composite materials. The available data included many variations of the manner in which the fibers were broken as well as many different matrix resins. Much of the discontinuous, aligned data was from a product form, DuPont's Long Discontinuous Fiber (LDF), that was not directly comparable in that the fibers were highly aligned and stretch-broken and the resin was thermoplastic. Nonetheless, the reported data revealed that stiffness retention properties for discontinuous fiber composite materials were achievable to the 90%+ level, supporting theoretical projections. Yet though the historical data and theory indicated that strengths exceeding 80% were possible, when the LDF product form was removed from the data the cumulative average strength retentions for discontinuous, unidirectional composite materials were only in the range of 60%.

Although initial carbon fiber chopping was successful, it was apparent early on in the program that the 12K carbon fiber tows utilized in the program did not mimic the gun-roving glass used in the P4 process. That is, typical glass gun-roving when chopped and sprayed through the P4 chopper gun will filamentize, whereas current commercially available carbon tow products remain intact as discrete, chopped, and, for lack of a better word, "logs" of carbon tow. The program investigated a variety of carbon fiber product forms, spray patterns, chopping parameters, sizing levels, and tow sizes. As most of the larger tows did not spread in the chopping and spraying process, the program moved toward chopping multiple 3K tows. The multi-tow incoming product form roughly approximated a more filamentized product like the gun-roving product forms being used very successfully with glass fibers and was the approach that the program used for the remainder of the feasibility assessment. During the course of the program, several chopping lengths, alignment mechanisms, and other variables were explored. However,

carbon fiber form development to achieve a more sprayable product was identified as a future need.

Numerous test panels were prepared by infusion of preforms fabricated using the P4A equipment to obtain property data. The bulk of the preforms were processed utilizing multiple 3K tows of TOHO's Besfight® G30-300 carbon fiber product form. Preforms were sprayed-up as unidirectional, $\pm 45^\circ$, or quasi-isotropic laminates utilizing 3M's PT-500® powdered binder during the consolidation portion of the process. After being consolidated, the preforms were RTM-infused with Shell Epon 862 with Curing Agent W. Irrespective of the fiber length, which ranged from 2 inches up to 5 inches, and other parameters explored, the measured stiffness properties for the P4A laminates were continually above 90% of the level expected for continuous fiber-reinforced composites. Yet the strength retentions observed for the uniaxial, 0° tension test coupons were consistently in the 50% range of continuous properties. Numerous factors to the currently achievable strength translations were identified and include issues associated with the carbon fiber product form currently being utilized, orientation affects, and binder/matrix interactions. Figure 3 graphically presents a "snap-shot" of the mechanical properties attainable with P4A as it exists today. Ongoing efforts are assessing the issue of the low unidirectional strength retentions.

3.2 Structural Complexities The ability of a process to enable or successfully fabricate structural complexities representative of the end use is critical and thus was defined as one of the four success metrics. Complexities representative of key or typical aerospace structures and that offered the most potential to exercise the process and assess its potential and limitations were carefully selected by the team. The complexities identified were T-stiffeners, curved beaded panels, and complex C-channels. The rationale behind these selections is provided in the following paragraphs.

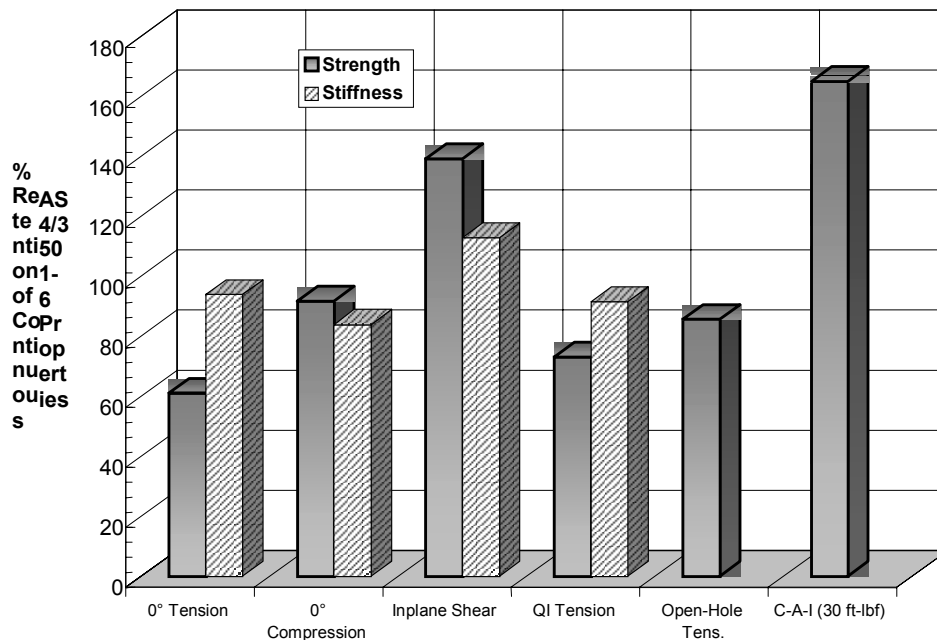


Figure 3. Comparison of P4A (G30-500/Epon 862) to Continuous AS4/3501-6 Properties.

3.2.1 T-Stiffeners T-stiffeners are commonly used in aerospace structures as a type of bonded joint or stiffener typically loaded in tension. It was also thought that P4A could offer a means to eliminate the need for costly secondary stiffening that can be required in the inherently resin-rich areas formed when fabricating T-stiffeners. One potential approach would be to spray-up very short fibers in the area commonly referred to as the “noodle area” (i.e., junction formed at the web/cap intersection). This complexity exercised the ability of the chopped carbon fibers to bend around very tight radii. Figure 4 is a schematic of the T-stiffener configuration and the approach taken to fabricate the preforms.

A limited number of P4A preforms were fabricated to investigate the affect of fiber length, fiber orientation, and noodle-area reinforcing. The carbon fiber utilized was TOHO’s Besfight G30-500 3K tow. The P4A preforms were RTM’d and tested at room temperature. Conventional T-stiffeners were also fabricated using commercially available carbon fiber fabric materials and braided noodle reinforcements to serve for comparison. Limited pull-off testing of both the P4A and baseline Ts was performed. Albeit very limited in scope and quantity, the testing showed initial failure stresses for the P4A T-stiffeners that were significantly lower than the baseline T-stiffeners.

3.2.2 Curved Beaded Panels The second complexity investigated was to be a curved beaded stiffened panel. Again, this was not only representative of aerospace structures, but also offered a structural concept that the process may enable. Conventional bead or hat-stiffening is a time consuming and/or costly process, and the stiffeners are often mechanically fastened, which adds both weight and fabrication cost. Additionally, fiber bridging can occur at the tight radii. The technical team felt that the discontinuous fiber and programming attributes of the P4A method

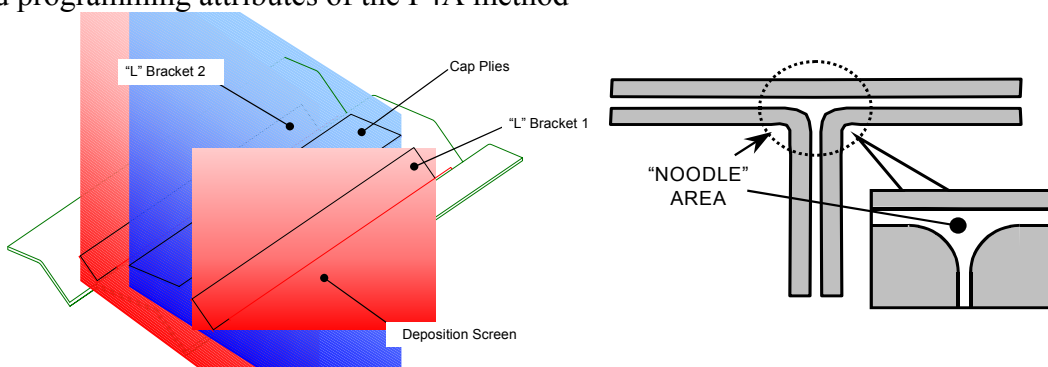


Figure 4. Schematic of T-Stiffener Preforming Approach.

might be ideally suited to fabricate such integrally stiffened preforms. Fortuitously, one of the components being considered by the P4A team as a potential process demonstrator article was a dorsal cover for the F18-E/F. This is a large, curved, and stiffened structure, which is currently a hand laid-up, graphite/epoxy component, which incorporates hat-

stiffeners as panel breaks. The stiffeners are both secondarily bonded and mechanically fastened to the interior surface of the dorsal cover. This structure was therefore selected to demonstrate curved, stiffened panels and was slightly redesigned to ensure that the design could take advantage of the process.

The design approach to the P4A article utilized two separate preforms: an outer mold line skin and an inner mold line skin. In order to fabricate the preforms, a low-cost, innovative deposition screen was constructed using perforated sheet metal stock. The preforming screen tool was reconfigured by using separate screen inserts in the areas where stiffening geometries were to be formed, allowing both the smooth outer mold line and the hat-stiffened inner mold line preforms to be produced in the same tool. Figure 5 is a photograph of the low-cost deposition screen utilized to process the F18 dorsal cover preforms. Aligned, oriented preforms were fabricated for the F18 dorsal cover and proved to be very amenable to the P4A process. This component offered the opportunity to fabricate and cost a full structure and will be discussed in more detail in later sections of this paper.

3.2.3 Complex C-Channel The last structural complexity was a complex C-channel. This was a fictitious configuration designed to incorporate several features oftentimes encountered in aerospace components. As can be seen from the sketch, shown in Figure 6, key features incorporated into this component include various sizes of radii; multiple bends; and tall, vertical, and slanted surfaces.

As was the case for the dorsal cover, low-cost deposition screen tooling was fabricated using perforated sheet metal stock. Of all of the shapes attempted during the course of this program, the complex C-channel proved to be the most difficult. A total of four complex C-channel preforms were fabricated with only one of the preforms incorporating aligned fibers due to challenges encountered with maintaining alignment on the vertical surface. The remaining three preforms were fabricated using randomly sprayed fibers and proved to be significantly easier to process.



Figure 5. Deposition Screen Utilized to Fabricate F18 Dorsal Cover Preforms (screen shown configured for inner mold line skin).

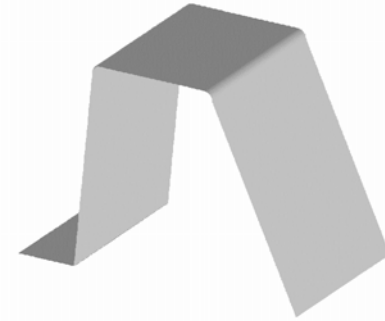


Figure 6. Schematic Representation of the “Complex C-Channel.”

Three of the preforms were VARTM infused and proved to be relatively easy to fully impregnate. Inspection of the cured complex C-channel revealed that there was poor definition in the various tight radii, and no testing was performed.

3.3 Structural and Costing Demonstrators Since the primary objective of the program was assessing P4 as an affordable aerospace method, the cost reduction potential needed to be demonstrated. The approach was to select an actual aerospace structure, redesign it for the process, and fabricate and cost it. A cost model was developed, which will be discussed in a separate section. Each of the airframer team members provided multiple candidate components for fabrication using the preforming process. A rigorous down-selection process led to two components being selected: the F/A-18 E/F dorsal cover and the C-17 tailcone.

3.3.1 F/A-18E/F Dorsal Cover The dorsal cover was representative of typical access doors on a high performance fighter. It is an actual production part on the F/A-18 E/F and is fabricated in production from prepreg. The cover brought with it the opportunity for actual production costs and weights as well as an available finite element analysis model. It also served to demonstrate enabling technology for beaded structure, as previously discussed. It is roughly 3 feet long, trapezoidal, with a maximum width of 18 inches. Aerodynamics drives its contour and aerodynamic loads and required buckling resistance drives its structural design, as shown in Figure 7.

As mentioned earlier, the outer and inner mold line skins were preformed at NCC using TOHO’s Besfight G30-500-3K carbon fiber, with 5% by weight PT-500 epoxy powder binder used in the preforming process. The two preformed skins were shipped to Northrop Grumman, where they were combined in the VARTM infusion tool. Nonstructural closed cell foam was placed within the stiffeners to prevent them filling with resin during the infusion process. The entire structure was infused with Cytec’s Cycom 823 epoxy resin in a heated tool. Figure 8 shows the outer and inner mold line surfaces of the VARTM-infused dorsal cover. The P4A design and the process’ ability to fabricate integrally stiffened skins eliminated the need for mechanical fasteners that exist on the baseline. Due largely to this feature, the P4A dorsal cover was 9% lower in weight than the baseline structure.

3.3.2 YC-15 Tailcone The C-17 tailcone was the highest ranked component against the criteria and was selected as the major structural demonstrator and the structure against which to validate the cost model. However, it was too large to be fabricated in the existing NCC advanced preforming facility. The YC-15 tailcone, a part of similar geometry but smaller dimensions, was substituted as the demonstration component. This not only offered essentially the same opportunity to assess the process as the C-17 component, but also offered the potential for flight demonstration if the YC-15 were returned to flying status. The YC-15 tailcone is approximately 4 feet in height and 4 feet in diameter at the base. The baseline design is a bonded rib-stiffened carbon fiber-reinforced epoxy. The P4A design is sandwich stiffened with balsa core between its inner and outer mold line skins. Due to some difficulties in fabricating the preforming tooling, a decision was made to make both the inner and outer mold line skins identical and to depend on the ability of the preforms to move to the proper contour during the VARTM process. The skins were preformed at NCC and sent to Northrop Grumman for VARTM infusion. Nondestructive evaluation of the tailcones was done by Boeing-Seattle. Six tailcones were successfully preformed and infused. Figure 9 is a photograph of both a full-sized tail cone and a sectioned tailcone revealing the balsa core.

The P4A tailcone design resulted in an 11% weight increase over the baseline structure due to anticipated P4A mechanical properties as well as added thickness in the cap area. It was felt that the weight could have been reduced via redesign and still meet the design requirements without excessive sacrifice in slightly increased cost, but time precluded such trades. One of the tailcones was successfully fit checked on the YC-15 aircraft.

3.3.3 Cost Model A cross-team cost model was developed for the P4A method with the goal of being able to predict the cost of the components to be produced during the course of the program. During the course of the program, an expert team was assembled; a best representation of the process flow was determined; cost drivers were identified; equations were written, along with time standards; and a working model was created in Microsoft Excel[®]. The model was then used to predict the cost to produce the structures to be fabricated. The selected structure was to then be fabricated and actual cost data collected to compare with and validate the model.

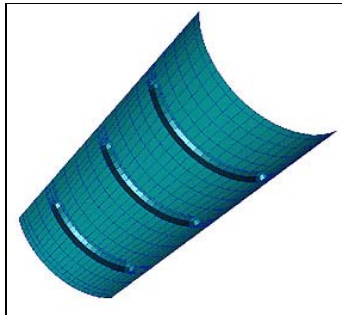


Figure 7. PATRAN Model of Hat-Stiffened Dorsal Cover.



Figure 8. F/A-18 E/F P4A Dorsal Cover.



Figure 9. Infused YC-15 Tailcones.

A cost study was conducted during every step of the preforming and infusion of the entire tailcone. The study was conducted by experienced Boeing costing personnel and included detailed time and motion studies at both NCC and Northrop Grumman. An estimate for the C-17 tailcone had been done initially. The actual time study data was then utilized to validate the cost model and resulted in no real modifications being required other than replacing some assumed values with actual data. Once the model was validated for the YC-15 tail cone fabrication, the model was rerun for the size and shape of the C-17 tailcone. The cost model projected that the P4A tailcone would be 84% lower in cost than its hand laid-up prepreg composite counterpart. Comparison of actual C-17 tailcone costs with the costs associated with actual P4A preforming and subsequent VARTM infusion was determined to be 83% lower in cost, assuming a 0.007 inch per ply

thickness in preforming. It should be noted here that the original P4A cost model for the YC-15 tailcone assumed a per ply thickness of 0.007 inch. However, actual ply thickness was nearly doubled. Therefore, in order to account for this discrepancy, the C-17 cost model was rerun using a ply thickness of 0.0035 inch, which was equivalent to doubling the number of passes required by the robot. Despite using a ply thickness of only 0.0035 inch, a cost savings of 80% was nonetheless realized. This relative insensitivity to the number of programmed passes reveals that the bulk of the time associated with P4A is attributable to set-up. Based on the excellent correspondence between the modeled and collected costs, the model is felt to be very representative of the process and therefore available for cost trades for potential P4A-fabricated structures. Based on this, there is a high degree of confidence that the C-17 tailcone cost reduction projections could be realized.

As the F/A-18E/F dorsal cover was an existing component with a cost baseline, its cost and weights were also tracked and compared to the baseline costs. The evaluation showed the P4A cover to be almost 48% lower in cost than the prepreg baseline. Of these savings, 64% was due to the P4A preforming process and 36% was due to the change to VARTM infusion. The ability to form integrally stiffened skins and eliminate fasteners not only impacted the weight but also contributed to the cost savings on this component.

4. SUMMARY

The assessment of the P4A was performed under a very aggressive schedule, and many of the developments undertaken on this program broke new ground. The results, therefore, should be viewed in light of the process maturity. Some of the challenges faced were a function of the prototype nature of the manufacturing cell, and many ideas for improvements were generated and some even incorporated in real time. Based on the success metrics, the P4A process is felt to offer significant cost savings for carefully selected aerospace structures. The mechanical properties are encouraging at this stage in the technology with the exception of unidirectional tensile strength. Data suggest that this material form may be more damage tolerant as well. However, additional work needs to be performed to determine the limits of tensile strength translation. Additionally, suitable carbon fiber product forms that are optimized for the process need to be investigated. The process is capable of handling typical geometries and even offering potential improvements for some structural concepts. Cost savings for certain structures can be dramatic, as demonstrated by the C-17 tailcone.

Another metric that was established by the P4A team was whether or not P4A was an *enabling* technology. During the performance of the program, the team identified several enablers garnered through the use of P4A. These enablers, listed in no particular order, include:

- • Incorporation of bead stiffening and potential for corrugated preforms
- • Easy inclusion of panel breaks in design
- • Elimination of fasteners

- • Utilization of potentially low-cost carbon fiber product forms
- • Fabrication of hybridized fiber preforms
- • A source of low-cost, complex preforms for the burgeoning increase in low-cost infusion technology
- • Part integration (through creative preform design)
- • High-production, low material wastage
- • Integration of sensors, wires, or other elements within the preform
- • Potential for flexible manufacturing cell

The development of a shared cost model across the team members was one of the major successes of the program. The program demonstrated rapid technology assessment and development that may have great value in reducing the time required to assess and apply advanced technologies. The majority of the effort was performed between July 1998, when the first carbon fiber preforms were fabricated, to August 1999, when the team performed the final technology assessment. The ability for such a large team to work closely as a “virtual company” was demonstrated, with team members from the airframers often on-site in the program office or on the shop floor at NCC. Working together in a pre-competitive manner was a very critical part of the success of this program, and the benefits of such interaction were well demonstrated. The future for P4A and advance preforming might hold much promise for low cost composites. Recent tests have shown potential for application to much thicker structures than have been made to date. Other potential opportunities outside of aerospace structures include shipping containers and portable shelters.

5. ACKNOWLEDGMENTS

This research was performed under US Air Force Contract No. F33615-97-C-5005. The close interaction of the team—the Air Force Research Laboratory, NCC, Boeing-Seattle, Boeing-St. Louis, Lockheed Martin, Northrop Grumman, and the University of Dayton Research Institute—is noteworthy and enabled the successes achieved on this effort.

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