Development of Textile Reinforced Composites for Aircraft Structures

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ABSTRACT

NASA has been a leader in development of composite materials for aircraft applications during the past 25 years. In the early 1980's NASA and others conducted research to improve damage tolerance of composite structures through the use of toughened resins but these resins were not cost-effective. The aircraft industry wanted affordable, robust structures that could withstand the rigors of flight service with minimal damage. The cost and damage tolerance barriers of conventional laminated composites led NASA to focus on new concepts in composites which would incorporate the automated manufacturing methods of the textiles industry and which would incorporate through-the-thickness reinforcements. The NASA Advanced Composites Technology (ACT) Program provided the resources to extensively investigate the application of textile processes to next generation aircraft wing and fuselage structures. This paper discusses advanced textile material forms that have been developed, innovative machine concepts and key technology advancements required for future application of textile reinforced composites in commercial transport aircraft. Multiaxial warp knitting, triaxial braiding and through-the-thickness stitching are the three textile processes that have surfaced as the most promising for further development.

Textile reinforced composite structural elements that have been developed in the NASA ACT Program are discussed. Included are braided fuselage frames and window-belt reinforcements, woven/stitched lower fuselage side panels, stitched multiaxial warp knit wing skins, and braided wing stiffeners. In addition, low-cost processing concepts such as resin transfer molding (RTM), resin film infusion (RFI), and vacuum-assisted resin transfer molding (VARTM) are discussed. Process modeling concepts to predict resin flow and cure in textile preforms are also discussed.

KEYWORDS: Textile Reinforced Composites, Braiding, Knitting, Stitching, Resin Transfer Molding, Process Modeling
film infusion (RFI), and vacuum-assisted resin 
transfer molding (VARTM) would be the keys to 
successful fabrication of composite structures from 
dry textile preforms.

This paper summarizes the development of advanced 
material forms, textile machine advancements, 
analytical process models, fabrication of aircraft 
structural components, and lessons learned working 
with various textile material forms, machines and 
processes.

2.0 TEXTILE MATERIAL FORMS AND 
STRUCTURAL ELEMENTS

As preliminary design databases were generated, 
NASA and the U.S. aircraft manufacturers began to 
focus on the textile processes that offered the most 
promise. The textile processes listed in figure 1 were 
evaluated. The advantages and limitations of each 
process were established and decisions on further 
development were made. The textile material forms 
shown in figure 2 have shown the most promise for 
application to aircraft structures. Multiaxial warp 
knitting is a highly tailor able automated process that 
produces multidirectional broadgoods for large area 
coverage. Two-dimensional and three-dimensional 
braids are used to create stiffeners, frames and 
beams with complex cross-sections. Through-the-
thickness stitching is an effective way to debulk 
preforms and to achieve improved out-of-plane 
strength and damage tolerance of composite 
structures.

The structural elements shown in figure 3 were 
selected by NASA and the aircraft manufacturers to 
demonstrate the applicability of textiles to fuselage 
structures. The combination of weaving and stitching 
was used to fabricate lower fuselage side panel 
preforms[4]. The fuselage panel shown in figure 4 
have four circumferential frames and four longitudinal 
stiffeners. The intersections of the woven stiffeners 
and frames have continuous fibers through the 
intersection to provide structural continuity. The 
flanges of the woven frames are stitched to the 
woven skin material. Braided frames were used to 
fabricate curved fuselage keel panels [5], a typical 
panel is shown in figure 5. The fuselage parts were 
fabricated with either matched metal heated RTM 
tooling or RFI autoclave processes.

Because of the high load intensity and the propensity 
for foreign object damage, NASA focused most of its 
textiles research on damage tolerant wing structures, 
figure 6. Since most of the wing weight is in the 
upper and lower cover panels of the wing, they are a 
logical choice for pursuit of cost and weight savings. 
Some of the global design considerations for wing 
panels include strength, stiffness, and damage 
tolerance. Based on tests conducted previously by 
NASA and Boeing (formerly McDonnell Douglas), 
through-the-thickness stitching was chosen for the 
wing cover panels because a 100-percent 
improvement in compression-after-impact strength 
compared to laminated tape composites could be 
achieved [6].

Blade stiffeners and integral spar caps were chosen 
by Boeing as stiffening elements for the upper and 
lower wing cover panels. The upper cover skin 
stiffener and spar caps are fabricated with Saertex 
multiaxial warp knit fabric. However, due to the 
curvature of the lower wing cover panel, contoured 
triaxially braided stiffeners were selected. The 
stiffeners and spar caps were stitched onto the wing 
skins to form integral wing cover panels with no 
mechanical fasteners.

Before proceeding to design and fabrication of a full-

scale wing box, Boeing fabricated a 2.4 m by 3.7 m 
stub box with the stitched/RFI process as shown in 
figure 7. An interior view of a stub box cover panel 
is shown in figure 8. This box was stitched with a 
computer controlled heavy duty single needle 
machine similar to those used in the quilting 
industry. The stub box was successfully tested at 
NASA Langley and met the design requirements set 
forth by Boeing for commercial transport wing 
structure.

3.0 ADVANCED TEXTILE MACHINE 
DEVELOPMENT

The development of a high speed multi-needle 
stitching machine and improvements in the 
multiaxial warp knitting process were required to 
achieve affordable full-scale wing structures. The 
stitching machine had to be capable of stitching 
cover panel preforms that were 3.0 m wide by 15.2 m 
long by .78 mm thick at speeds up to 800 stitches 
per minute. The multiaxial warp knitting machine 
had to be capable of producing 2.5 m wide carbon 
fabric wth an areal weight of 1425 g/m². The 
advanced stitching machine shown in figure 9 was 
developed by Ingersoll Milling Machine Company to 
meet the requirements of a full-scale wing box [7]. 
The high speed stitching heads were developed by 
Path Industries, Inc. The lower cover preform for 
the full-scale wing box is shown on the stitching 
machine bed in figure 9.

Multiaxial warp knitting is a highly automated 
process for producing multilayer broadgoods. 
Compared to woven broadgoods, the knitted fabrics 
have less crimp since the individual tows are not 
interlaced. Early machine concepts lacked proper
tension control to maintain fiber alignment. Saertex and Liba teamed up to upgrade tension control mechanisms and to improve overall quality of carbon fabrics. A schematic of the Saertex/Liba machine is shown in figure 10. This machine can produce 5-ply carbon fabrics in one pass through the machine. A two-step process is required to produce a 7-ply fabric for the Boeing full-scale wing cover panels. Splicing concepts have been developed to produce fabrics up to 2.5 m wide.

4.0 FABRICATION OF TEXTILE REINFORCED COMPOSITES

Three resin transfer processes are commonly used to produce composites from dry textile preforms: (1) resin transfer molding (RTM), (2) resin film infusion (RFI), and (3) vacuum assisted resin transfer molding (VARTM). RTM is a good process to achieve high fiber volume fraction for complex shapes such as the curved fuselage frames shown in figure 5. RTM requires the use of expensive matched metal heated tools, such as Invar, and high pressure to pump liquid resin into net shape tools. High quality parts can be achieved but the cost is prohibitive for large parts such as wing skins.

RFI is a process being pursed by NASA and The Boeing Company to develop cost-effective wing structures for commercial transport aircraft [8]. The RFI process developed by Boeing consists of an outer mold line tool, an epoxy resin film, a near net shape textile preform, an inner mold line tool and a reusable vacuum bag. Resin slabs are placed on the outer mold line tool and the preform and inner mold line tools are placed on top of the resin. The entire assembly is covered with a reusable vacuum bag and the part is placed inside an autoclave. After the resin is melted, vacuum pressure is used to infuse resin into the preform. Once infiltrated, the part is cured under pressure and temperature in an autoclave. The keys to producing aircraft quality parts with the RFI process are understanding the compaction and permeability characteristics of the preform and understanding kinetics and viscosity profiles for the resin as a function of temperature. Figure 11 shows a full-scale 13 m long stitched/RFI wing cover panel fabricated by Boeing under contract to NASA. The one-piece reusable vacuum bag used to cure the cover panel is shown in figure 12.

VARTM processes have been used for many years to fabricate fiberglass reinforced composite structures. The U.S. Naval Surface Warfare Center in Bethesda, MD has been the major promoter of this technology for composite marine applications [9]. The major advantages of VARTM processes compared to conventional autoclave processes are the lower cost of tooling, reduced cost of energy to cure composite parts, and almost unlimited part size (i.e., no size constraints based on the size of the autoclave). Until recently, VARTM was primarily used to fabricate glass reinforced polyester and vinyl ester composites. However, due to recent developments in resin and preform technologies, aircraft manufacturers are beginning to show significant interest in VARTM processes for graphite-epoxy and graphite-bismaleimide composite systems. One drawback to VARTM processes has been low fiber volume fraction compared to the higher fractions achievable with autoclave pressure. However, stitching and debulking methods have been developed to achieve preforms that are near net shape with little or no further compaction required during processing.

NASA has conducted contractual research with Seemann Composites, Inc. to establish the feasibility of their VARTM process to produce aircraft quality composite structures. Their proprietary process, called SCRIMP (Seemann Composites Resin Injection Molding Process) utilizes a resin distribution media to achieve full wet-out of the preform, figure 13. In addition, Seemann has developed a reusable bagging concept that eliminates most of the costs associated with conventional bagging procedures. Seemann Composites has also demonstrated SCRIMP for lightly-loaded general aviation aircraft structures. Figure 14 shows the one-sided tooling concept and the graphite preform for a small aircraft fuselage section and figure 15 shows the completed graphite/epoxy part after resin injection and cure. Current and future tooling developments for integral heating will eliminate the need for oven cure and postcure of composite parts fabricated with VARTM processes.

NASA is also investigating the feasibility of SCRIMP to produce aircraft quality heavily-loaded primary structures. Additional technology development is required to achieve dimensional control and acceptable fiber volume fractions for thick structural elements. Innovative tooling concepts will be required to meet typical assembly tolerances for aircraft structures. Stitching will be required to achieve near net shape prior to resin injection. The reusable bagging concept for a three stringer panel representative of wing structure is shown in figure 16. The ease of removing this bag from the stiffened panel is illustrated in figure 17, and the finished panel (after resin injection and cure) is shown in figure 18.

To eliminate trial and error processes, analytical models are required to predict resin flow into textile
resin starved areas must be developed and repair concepts must be developed. Methods to reinfuse large expensive parts is not an option, repair and handling damage will occur. Since scrap of and to reduce costs. Invariably, processing defects inspection techniques are needed to minimize scrap addition, more stringent in-process controls and complex shape aircraft structural preforms. In produce the desired fiber architectures for all learned to-date indicate that no one machine can considerably when carbon fibers were used. Lessons showed a lot of potential but available machine boundaries. Two- and three-dimensional braiding showed a lot of potential but available machine capacity limited the architecture and the size of the preforms that could be achieved. Folding or postforming of triaxial braided preforms offered the most flexibility in achieving small cross-section complex shapes. Multiaxial warp knitting proved to be the best process for large area multiaxial multilayer broadgoods but structural shapes had to be achieved through postforming and stitching. Through-the-thickness stitching proved to be the best textile process to achieve improved damage tolerance. Compared to processing with glass fibers, all textile machines investigated had to be slowed considerably when carbon fibers were used. Lessons learned to-date indicate that no one machine can produce the desired fiber architectures for all complex shape aircraft structural preforms. In addition, more stringent in-process controls and inspection techniques are needed to minimize scrap and to reduce costs. Invariably, processing defects and handling damage will occur. Since scrap of large expensive parts is not an option, repair concepts must be developed. Methods to reinfuse resin starved areas must be developed and repair concepts to restore damaged structure to original strength must also be developed.

Analytical models are required to eliminate costly trial and error processes that are frequently used in tool design and development of processing cycles. Resin viscosity and cure kinetics must be characterized to consistently achieve high quality composite parts. Since compaction and permeability behavior are different for each fiber architecture and preform configuration, empirical relationships must be developed for input to analytical models.

Tooling concepts that can accommodate variability in dry preform bulk and permeability must be developed to achieve uniform resin flow and fiber wet-out. Dimensional tolerances on tooling is critical to avoid racetracking or short circuiting of resin during the infusion process. Further development of compaction methods and soft tooling concepts such as VARTM will lead to reduced scrap and lower manufacturing costs.

5.0 LESSONS LEARNED FROM TEXTILE DEVELOPMENT

Early attempts to develop complex equipment to fabricate near net shape multidirectional multilayer fabrics were unsuccessful. This result was primarily caused by the fact that various textile technologies were being stretched beyond their technical boundaries. Two- and three-dimensional braiding showed a lot of potential but available machine processing costs for large area composite structures.

6.0 CONCLUDING REMARKS

Major advancements in the development of textile preforms in concert with resin transfer tooling concepts makes it feasible to fabricate high quality damage tolerant aircraft structures with these material forms and processes. Recent developments in improved tension control of tows in the multiaxial warp knitting process have made this the material of choice for large area multidirectional broadgoods. Innovative tooling concepts have been developed to produce curved braided preforms for application to fuselage frames and wing stiffeners for commercial transport aircraft. NASA and Boeing have demonstrated that through-the-thickness stitching of dry textile preforms can provide a 100-percent increase in damage tolerance of composite wing structures compared to laminated tape construction techniques.

Recent investments in a second generation stitching machine with multiple heads are expected to pay-off in terms of improved quality, higher speed, and lower cost. Low cost resin transfer molding processes are now being applied to fabrication of aircraft quality, heavily-loaded primary structures. Modeling studies of resin transfer molding will focus on prediction of resin flow into complex textile preforms to insure high quality, high speed fabrication at lower costs. Additional development of out-of-autoclave vacuum-assisted resin transfer molding (VARTM) processes could lead to significantly lower tooling and fabrication costs for large area composite structures.
7.0 REFERENCES


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<tr>
<th>Textile Process</th>
<th>Advantages</th>
<th>Limitations</th>
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<td>Low Crimp Unwoven</td>
<td>High in-plane properties</td>
<td>Low transverse and out-of-plane properties</td>
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<td>Good tailorability</td>
<td>Poor fabric stability</td>
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<td></td>
<td>Highly automated preform fabrication process</td>
<td>Labor intensive lay-up</td>
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<td>2-D Woven Fabric</td>
<td>Good in-plane properties</td>
<td>Limited tailorability for off-axis properties</td>
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<td>Good drapeability</td>
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<td>Highly automated preform fabrication process</td>
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<td>Integrity woven shapes possible</td>
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<td></td>
<td>Suited for large area coverage</td>
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<td>Extensive data base</td>
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<td>3-D Woven Fabric</td>
<td>Moderate in-plane and out-of-plane properties</td>
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<td>2-D Braided Preform</td>
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<td>Well suited for complex curved shapes</td>
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<td>3-D Braided Preform</td>
<td>Good balance in in-plane and out-of-plane properties</td>
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<td>Slow preform fabrication process</td>
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<td>Size limitation due to machine availability</td>
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<td>Multiaxial Warp Knit</td>
<td>Good tailorability for balanced in-plane properties</td>
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<td>Highly automated preform fabrication process</td>
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<td>Multi-layer high throughput material suited for large area coverage</td>
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<td>Stiching</td>
<td>Good in-plane properties</td>
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<td>Highly automated process</td>
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<td>Provides excellent damage tolerance and out-of-plane strength</td>
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<td>Small reduction in in-plane properties</td>
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<td>Poor accessibility to complex curved shapes</td>
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Figure 1. Application potential of textile reinforced composite materials for aircraft structures.

Figure 2. Textile material forms.
Figure 3. Application of textile reinforced composites in fuselage structures.

Figure 4. Woven/stitched lower fuselage side panel preform.

Figure 5. Curved braided frames for fuselage keel structure.

Figure 6. Application of textile reinforced composites in wing structures.

Figure 7. Stitched/resin film infused wing stub box.

Figure 8. Interior view of stub box cover panel.
Advantages of low-cost RTM process:
- Resin and fiber used in lowest cost form
- Prepreg process eliminated
- Freezer storage & shelf life problems eliminated
- Low cost, one-sided tooling
- Low energy, low pressure out-of-autoclave processing
- Utilizes net-shape, damage tolerant textile preforms
- Large integral structure minimizes secondary bonding and fastening

Challenges for aircraft applications:
- Out-of-autoclave cure resins with adequate properties
- Dimensional tolerances with low-cost tooling
Figure 15. Vacuum-assisted resin transfer molded fuselage section.

Figure 16. Reusable vacuum bag for VARTM of 3-stringer panel.

Figure 17. Removal of reusable vacuum bag from VARTM stiffened panel.

Program Structure
- Flow
- Heat Transfer
- Resin Kinetics
- Resin Viscosity
- Preform Compaction
- Residual Stress and Warpage

Ply Drop Off Single Blade Stiffener
Preform/Tooling Assembly

Figure 18. Stiffened panel fabricated by VARTM.

Figure 19. Three-dimensional resin film fusion model.