INNOVATIVE MANUFACTURING PROCESSES FOR A LIGHTWEIGHT, AFFORDABLE COMPOSITE HELICOPTER AIRFRAME

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Abstract

The Rotary Wing Structures Technology Demonstration program was a cooperative agreement, DAAH10-98-2-0002, between the U. S. Army Aviation Applied Technology Directorate in Fort Eustis, Virginia, and The Boeing Company. The objective of the program was to demonstrate advanced design and analyses tools, and manufacturing processes. The viability of the tools and processes to significantly reduce weight, manufacturing labor hours and engineering development time of composite structures for rotary-wing aircraft were to be demonstrated through the fabrication of a full-scale article. An Integrated Product Team applied Integrated Product and Process Development tools to execute the program. The program selected the 14-foot long center fuselage of the Apache helicopter for demonstration. Boeing successfully designed and manufactured a composite center fuselage that could replace the heavier and more costly aluminum structure of the existing AH-64 Apache helicopter. The new cocured and cobonded skin-stringer-frame subassembly is 28% stronger to accommodate the anticipated higher loads of the next-generation Apache helicopter. The demonstration article validated the 25% touch-labor cost savings and 15% weight reduction goals of the program. The key to reducing the recurring cost was a 75% reduction in fasteners and 73% reduction in parts achieved through a combination of innovative design concepts and the advanced composite manufacturing processes. The design was a center fuselage of unitized construction manufactured with Vacuum-Assisted Resin Transfer Molding; stitched carbon preform; and pressurized Resin Transfer Molding. In addition to reducing the recurring manufacturing cost, the program also reduced the high non-recurring cost of tooling for composites.

Introduction

The Rotary Wing Structures Technology Demonstration effort between the U. S. Army Aviation Applied Technology Directorate (AATD) and The Boeing Company. The objectives of the program were to apply advanced design and manufacturing tools in a virtual product environment to significantly reduce the weight and recurring manufacturing labor-hours for a composite helicopter fuselage. In addition, the program had to demonstrate rapid development and lower engineering cycle-time. Boeing demonstrated the improved cost and weight savings on the AH-64 Apache center fuselage, a 1970's design. The metrics of the exit criteria are a 42% reduction in recurring labor-hours and a 27% reduction in weight. These metrics were monitored continuously during engineering and manufacturing development, and were validated on the demonstration article.

The tools and processes to develop the design, to conduct the analyses and to manufacture the center fuselage of the Apache helicopter are discussed in the paper. The discussion then continues with details of the selected design, the tooling and the manufacturing. The paper concludes with the metrics of the manufactured fuselage. The manufacturing process, the fabrication of the demonstration article, and final validation of the metrics are described in Ref. 1.

Baseline Helicopter Structure

The structural basis for the program was the center section of the fuselage of the AH-64D Apache Longbow helicopter. The baseline helicopter structure for the metrics and exit criteria for the RWSTD program was a 1994 Technology Baseline derived from the structural basis. The 1994 Technology Baseline is described below.

The AH-64D helicopter has a structural design gross weight (SDGW) of 14,670 pounds. The center section, which forms the structural basis for the RWSTD program, extends from Station 115 to Station 280. It is a skin-stringer design of metal

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construction. The location and a detail view of this 14-foot center fuselage are shown in Fig. 1.

The metal center fuselage consists of 485 parts. The major structural components are four bulkheads, nine frames, and the integrally stiffened skin. In addition there is a deck, bulkhead and floors of the pilot's cabin area, and numerous intercostals, brackets, fittings and mounts. Each of the four bulkheads is machined as one-piece from an aluminum plate. The nine frames are assembled from multiple sheet metal details. Extruded aluminum stringers reinforce the skin, which has a surface area of 120.9 square feet. Each section of the skin is chem-milled to minimize weight. Several secondary components are made of Kevlar®. These components are assembled with 12,100 fasteners. Ballistic protection is provide by sixty foam blocks lining the inner surface of the skin; but these are not part of the baseline.

The metal center fuselage weighs 408 pounds. The recurring labor cost to fabricate the first unit (T-1) was 15,140 hours, which normalizes to 37.1 hr./lb. The composite content of the center section of the AH-64D fuselage is 3 percent.

The center section of the fuselage is the heart of the Apache helicopter. It reacts all major structural loads of the helicopter, accommodates major systems and supports all control linkages for their operation. The structural loads reacted by the center fuselage are shown in Fig. 2. The loads are from the rotor, the transmission, the engines, the reactions from the weapons through the pylons and wing, normal and crash landings, seat supports and side avionics bays. In addition to the loads, the center section of the fuselage supports the weights of all the major systems.

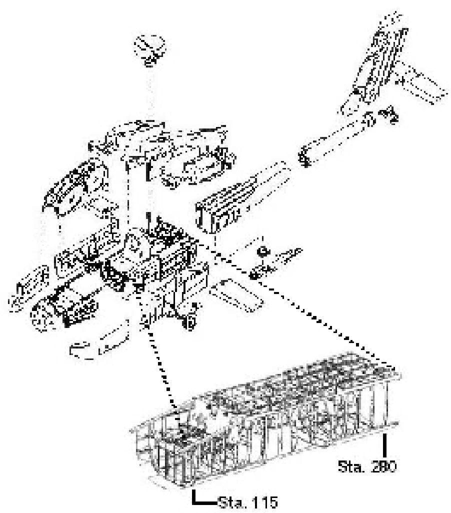

Fig. 1 The Apache center fuselage to be re-engineered for RWSTD program

The challenge in re-engineering the center fuselage to a composite structure was that all existing systems had to be accommodated exactly as in the metal configuration. The systems included are the forward and aft fuel cells, ammunition magazine and its feed, fuel transfer lines, flight controls and electrical harnesses. The structure supporting the fuel cells are designed to react the high transient load from hydrodynamic ram effect when the fuel cells are ballistically punctured. The RWSTD center fuselage was designed to maintain the interfaces with the forward and aft sections of the metal fuselage.

1994 Technology Baseline.

The Apache helicopter is a 1970s design with 3% composite content by weight in the fuselage. For the RWSTD program, the metal center fuselage was "redesigned" with 1994 technology. This is the 1994 Technology Baseline. The weight and cost estimated for the Baseline established the metrics and exit criteria for the RWSTD program. The differences between the existing metal center fuselage and the 1994 Technology Baseline are given in Table 1.

Table 1 The 1994 Technology Baseline

Existing Metal Center Fuselage	**1994 Technology Baseline Center Fuselage**
Designed for a SDGW of 14,670 lb.	Designed for a SDGW of 19,000 lb.
3% Composite by Weight	67% Composite by Weight
485 Parts	169 Parts
12,100 Fasteners	6,400 Fasteners
408 lb. Weight	351.4 lb. Weight
15,140 Recurring Manufacturing Man-Hours for T-1 Unit	11,708 Recurring Manufacturing Man-Hours for T-1 Unit

Metrics and Exit Criteria

The RWSTD metrics, selected with respect to the 1994 Technology Baseline, emphasize affordability and lightweight construction for the re-engineered RWSTD composite fuselage. The exit criterion for weight was a reduction of 15% (to 298.7 lb.). The exit criterion for the recurring labor hours for the first unit, T-1, was a reduction of 25% (to 8,781 hours). However, for the RWSTD center fuselage a "P-1" exit criterion was established from the T-1 hours. The P-1 hours are the T-1 hours minus the additional hours computed from quality and realization factors. P-1 hours, therefore, represent only the recurring touch labor hours for manufacturing. The P-1 exit criterion was 6,454 hours. The metrics for the RWSTD exit criteria are given in Table 2. The program also required a 40% reduction in non-recurring engineering development hours by reducing risk and increasing design efficiency with advanced tools, parametric modeling and simulation. Additional program metrics included improved structural integrity, on-condition repairability, and maintaining the baseline vulnerability capability.

Table 2 Metrics for Exit Criteria

Criteria	1994 Technology Baseline	RWSTD Exit Criteria (and % Change)
Weight, lb.	**351.4**	**298.7 (– 15%)**
T-1 Labor Hours	11,708	8,781 **(– 25%)**
P-1 Labor Hours (T-1 minus Quality and Realization Factors)		**6,454**

Approach

In order to meet the exit criteria and to satisfy the imposed constraints, Boeing identified a suite of Integrated Product and Process Development (IPPD) tools for the Integrated Product Team (IPT) to re-engineer the center fuselage. The IPT consisted of engineers from several Boeing sites, the U. S. Army and the sub-contractor Intellitec. The IPPD tools, exercised in a virtual product environment (VPE), allowed all disciplines to efficiently communicate with one another and work concurrently from design to manufacturing while remaining focused on the program goals and objectives.

Boeing initiated the program by first identifying cost drivers in order that the lowest possible cost is built into a quality product. Manufacturing proof articles were fabricated and tested in order to mitigate

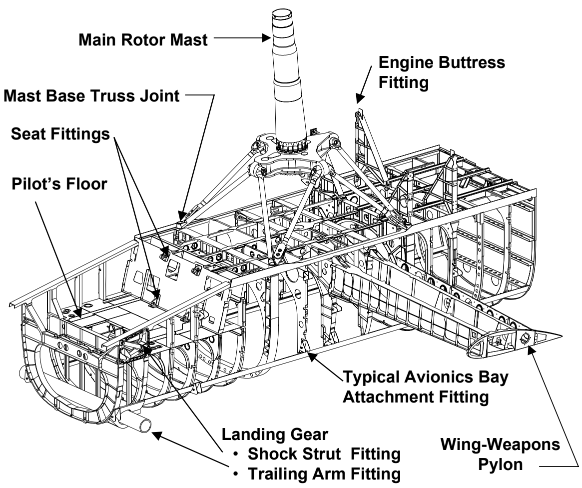

Fig. 2 Loads reacted by the center fuselage

structural and manufacturing risks. Preliminary design and extensive analysis followed. The results from the development activity were used to mature the manufacturing processes and provide the IPT with the confidence needed to ensure that the exit criteria would be achieved or exceeded.

Detail design was defined digitally in three dimensions. This definition was supported by high fidelity structural analysis, tooling, manufacturing and dimensional management during the entire design phase. Modeling and simulation in the VPE predicted and controlled form, fit and function, and established the assembly process and sequence. The metrics and exit criteria were continuously estimated during the preliminary and detail design phases.

IPPD Suite of Tools

The IPPD suite of tools selected was Boeing's Design, Manufacturing and Producibility Simulation (DMAPS). DMAPS is a design development environment, which enables inter-disciplinary communication and information exchange with the use of a common 3D geometric database as the "language" for all disciplines. Since all design information are embedded in 3D computer-aided design (CAD) models, redundant design definitions for manufacture and quality inspections are eliminated, conflicting design information are removed, and development time is shortened. Cost is, thereby, reduced. The DMAPS methodology was used to re-design of the Apache fuselage for higher performance and for the best use of available manufacturing processes to minimize cost and weight for a quality product. Knowledge-based engineering (KBE) tools were used to optimize the design for weight and cost, automatically generate molding surfaces, and provide outputs for machining and fabrication. Details of IPPD tools and the design methodology for an affordable, lightweight design are given in Ref. 2 and 3. Descriptions of how KBE tools and parametric modeling were used to optimize the RWSTD design of the center section are given in Ref. 4.

Down-Selection of the Structural Configuration

Five levels of Quality Function Deployment (QFD) were conducted at the beginning of the program to determine the "best" structural configuration. The IPT scored and ranked in great detail structural concepts and configurations, tooling approaches, manufacturing processes, and assembly methods and sequences required to achieve the program goals in terms of the technical and design requirements. After four levels of QFD, five sub-configurations of Configuration 27 were selected for further evaluation.

Sub-Configurations 27A through 27E shared the same common structural arrangement of skins, stringers, frames and bulkheads, and deck; since these assured the system and structural constraints of the heritage metal fuselage would be observed. These also had full-length skins with cocured or cobonded stringers to reduce or eliminate additional weight that would be incurred if primary load paths were spliced.

The main difference between the five configurations was the choice for assembling the center fuselage. Configurations 27A and 27B had one-piece integrally stiffened skin. The frames were integral with the skin in Configuration 27A, but were precured and cobonded in Configuration 27B. Configurations 27C and 27D were similar to Configurations 27A and 27B, respectively, except that the skin was longitudinally spliced for greater accessibility. Configuration 27E had a one-piece skin but spliced transversely at the pilot's floor. The precured two-piece frames and bulkheads were to be cocured to the skin. Schematic views of the five configurations are shown in Fig. 3. A female mold tool was common to all variations of this configuration.

Configuration 27B was evaluated for three different manufacturing and assembly methods. Configuration 27B-1 was a low-risk approach with precured fiber-placed skins and stringers, and where the frames and bulkheads were cobonded using trapped rubber tooling. Configuration 27B-2 was a high-risk approach where the fiber-placed skin, prepreg stringers and prepreg frames and bulkheads were cocured in a conventional autoclave. Configuration 27B-3 was a medium-risk approach where precured frames and bulkheads were cobonded to a stitched skin-stringer preform using RFI or VaRTM advanced composite process. Configuration 27B-3 would result in a unitized construction with reduces parts count and lower manufacturing labor hours.

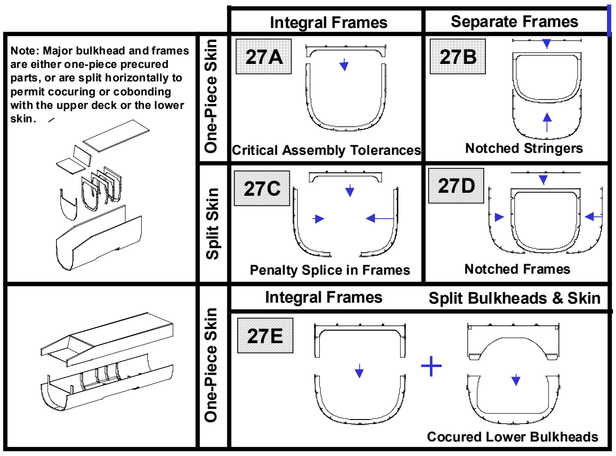

Fig. 3 Five structural configurations of Configuration 27

Cost and weight estimates were used to further discriminate the fabrication methods for each configuration. The fabrication methods evaluated were fiber placement, trapped rubber tool curing, stitching preforms, resin film infusion (RFI), vacuum-assisted resin transfer molding (VaRTM), hot drape forming and hand lay-up. The assembly methods evaluated were cocuring, cobonding, and mechanical fastening.

The rules, established for bonding or mechanical fastening, were the basis for the assembly evaluations. In general, those manufacturing concepts that did not stitch the preform were penalized with anti-peel fasteners at stringer-to-frame intersections in order to improve joint integrity, ballistic tolerance and post-buckling strength of skin panels. Also, secondary bonding of most precured parts was assumed to be impractical due to difficulties of holding the required gap tolerance of 0.010 inch for film adhesives. Thus, fasteners and liquid shims were assumed in these situations unless a flexible design concept was established to force tolerances to 0.010 inch or less.

In order to down-select a configuration, detailed structural information, simulation and assembly rules were used to develop ply lay-ups for, and analyze, the major structural components. Modeling was used to estimate their weight, and tooling and manufacturing models were used to plan the manufacturing processes and estimate the cost. Configuration 27B-3 was selected because it had a lower estimated risk, and lower weight and cost. The risk in comparison to the weight and cost of each of the last configurations is given in Fig. 4. The overall structural and manufacturing concepts of Configuration 27B-3 are schematically summarized in Fig. 5. The selection of the preferred configuration was based on the exit criteria and to produce the most affordable structure with first-time quality.

<u>Manufacturing Processes</u>. Three manufacturing processes were identified for Configuration 27B-3: RTM, VaRTM and RFI. RTM for the frames and

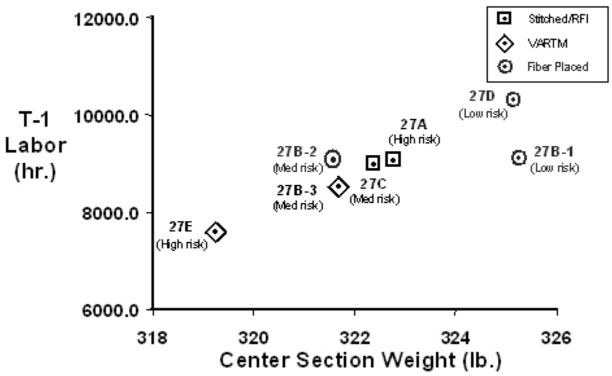

Fig. 4 Weights, cost and risks of Configuration 27

bulkheads was not assessed because of its maturity. The liquid molding VaRTM and RFI processes were assessed for the method of fabricating the components, and the consequence of the method(s) for assembling them. The components initially selected for the liquid molding process were the integrally stiffened skin, the deck, the canted bulkhead and the pilot's floor.

Preform Material Form. The issues for the preform are strength and weight, as well as formability, handling, sizing, stacking to assigned orientation and location, and stitching; all of which affect dimensional stability, fiber distortion, fiber loss along edges and preparation times. To satisfy these requirements, two thin, lightweight warp-knit stacks in collaboration with Saertex of Saerbeck, Germany, were developed. The final preform was stitched to improve handling and assure the structural integrity of joints. The stacks are made of unidirectional and plain weave carbon. The lay-ups are $[+45°/-45°/(0°-90°)^{PW}]_S$ and $[+45°/-45°]_S$, and the weights are 978 gm/m^2 and 592 gm/m^2, respectively, for unit widths of 1,270 mm.

Resin System. The objectives in resin selection were a low-cost, robust system for VaRTM or RFI processing with good mechanical properties. The processing characteristics of seven resin systems were initially evaluated, from which SI-ZG-5A epoxy from A.T.A.R.D. Laboratories of Lincoln, Nebraska, was selected. SI-ZG-5A processes at room temperature, cures at 250° F rather than 350° F which extends tool life. It has mechanical properties comparable to current advanced resin systems and can be stored for one year at room temperature. The moisture absorption for cured laminates is low at 0.8 percent.

Stitching Thread. Four threads were evaluated, each 1500-1600 denier thick: Kevlar 29, Kevlar 49, Zylon (a polybenzoxazole), and Vectran (a liquid crystal polyester). All threads had a PVA finish. Vectran was selected because of improved compatibility between the thread and the surrounding matrix and because, on earlier studies, it showed substantially improved strength and reduced moisture absorption.

Down-Selection of Liquid Molding Process

The development of the RFI and VaRTM liquid molding processes was key to reducing parts and fastener counts by enabling the high degree of structural unitization proposed in Configuration 27B-3. To mature these processes to a production-ready state for typical helicopter fuselages, advances were needed in resins, cure cycle, and tooling and bagging techniques. The differences in the RFI and VaRTM liquid molding processes are discussed below only in terms of the risks to the RWSTD program, and their possible influences on product quality and exit criteria.

In the RFI process, the resin is in the form of tiles placed under the preform and on the outer mold line (OML). During infusion, the resin melts into the preform, and the deeply curved preform, typical of helicopter fuselages, moves down on to the OML. This movement of the preform was considered high risk in dimensional control without extensive manufacturing development tests. Because of this risk in the RFI process, the VaRTM process was selected for the RWSTD program. The VaRTM process also avoids the additional cost of an autoclave. At the time, development tests for the VaRTM process were still required to validate the integrity of large, complex, deeply curved, unitized structures of aerospace quality. Further development was also required in tooling for tighter dimensional control, in ergonomics for assembling mandrels and bags, in cobonding and cocuring joints subjected to high loads, and in bagging concepts for a large integrally stiffened structure.

The Design of the RWSTD Center Fuselage

High-fidelity, three-dimensional, parametric models and knowledge-based engineering tools enabled the

- **RFI or VaRTM Skin co-cured with stitched stringers and tie-angles for frames and bulkheads**
- **RTM 1-piece Bulkheads**
- **RTM Canted Bulkhead with co-bonded intercostals**
- **RFI or VaRTM or RTM Frames**
- **RFI or VaRTM Deck with co-cured stringers and fuel cell support structure**
- **RFI or VaRTM Pilot's Floor with co-cured stringers**

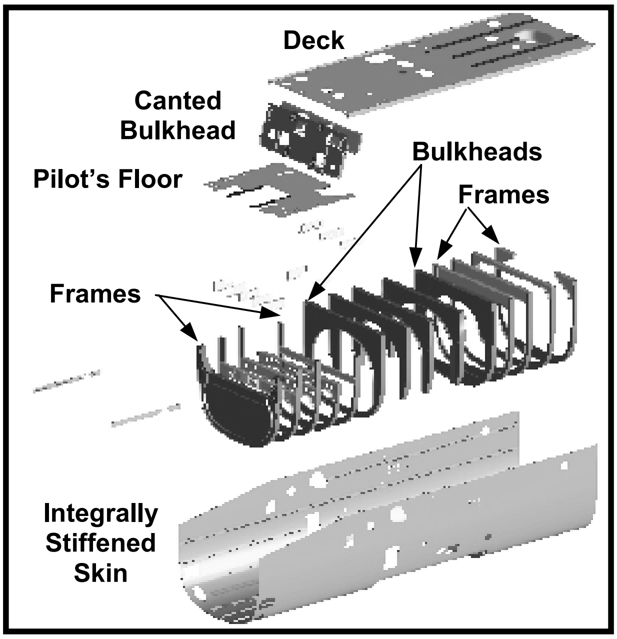

Fig. 5 Structural and manufacturing concepts of Configuration 27B-3

IPT to develop the design through rapid iterations. This capability also reduced the time required to complete the full engineering definition. The design tools also supported manufacturing and tooling with inputs for

- numerically controlled stitching, ply cutting and high-speed machining,
- laser projection for ply lay-up and trimming;
- manufacture of the VaRTM bag master, mandrels, molds and tools,
- rapid definition of frame and bulkhead geometries for modular RTM tools; and
- model-based definition (MBD) to support lean tooling approach for final assembly.

The loads for design and analysis were for a growth Apache helicopter with a structural design gross weight (SDGW) of 19,000 lb. These were determined by simulating the flight loads from the AH-64D Apache Longbow, which has a SDGW of 14,670 lb., and by distributing the mass representing the 19,000 lb. of the RWSTD configuration. The resulting finite element model of the helicopter was used to calculate the internal loads. The maximum load on the RWSTD center fuselage increased by 111% over that on the Apache Longbow helicopter.

The design features of the major structural items of the RWSTD center fuselage are described below. These are the frames and bulkheads, the skin-stringer lower fuselage and its infusion to form the unitized skin-stringer-frame structure, fittings, upper deck, metal components and assembly. An overview of the center fuselage is shown in Fig. 6.

Frames and Bulkheads

Thirteen frames and bulkheads were designed for the RTM process. The frames and bulkheads are semi-circular, four feet in diameter and four feet high. Eight frames were fabricated in one base mold with sets of inserts for each frame geometry. Similarly, four bulkheads and one frame were fabricated, with their respective inserts, in a second base mold. The modular RTM tooling was accurate and made it affordable to develop the RWSTD prototypes. The frames and bulkheads are made of 0.0082-inch thick plain weave carbon, and infused with 3M's PR 500 resin system. The thickness of the frames range from 0.0328 inch to 0.1200 inch, and those of the bulkheads from 0.0328 inch to 0.4080 inch. The dimensional tolerance was 0.005 inch. The RTM-cured frames and bulkheads were assembled between a pair of tie-angles in the skin preform of the fuselage, and cobonded when the skin was infused during the VaRTM process, Fig. 7. The modular RTM tooling is described in greater detail in Ref. 3.

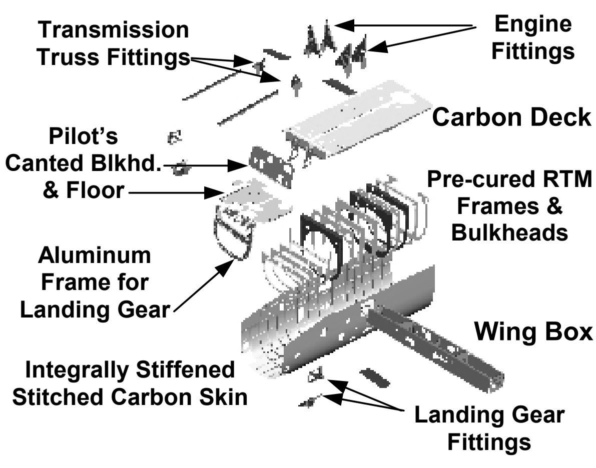

Fig. 6 Exploded view of RWSTD center fuselage

Skin-Stringer Lower Fuselage

Since the skin accounts for nearly 30% of the target weight metric, the re-design of this sub-assembly was significant and key to achieving the 25% weight reduction. Its size of 10 feet by 14 feet and a minimum gage thickness in the metal design resulted in a post-buckled design of highly tailored composite skins. Preforms of 31 stringers and 24 frame-tie angles were stitched to the skin preform. The frame-tie angles help to locate frames and bulkheads accurately. The design of the skin was optimized by the knowledge-based tool Parametric Composite Knowledge System (PACKS). Initially the skin was tailored with 108 ply stacks for 191 regions, and weighed 62.1 lb. The large number of stacks and regions made the assembling of the reform very labor intensive. The final result, after multiple PACKS, analysis, and producibility iterations, reduced the number of regions to 44 with 33 ply stacks and a weight of 63.3 lb. This marginal increase in weight, however, reduced the manufacturing labor hours significantly. Wire-frame images of the design evolution are shown in Fig. 8. A detailed description of the application of KBE tools that resulted in the optimized configuration is given in Ref. 4. By cobonding the frames and bulkheads when the skin-stringer preform was infused,

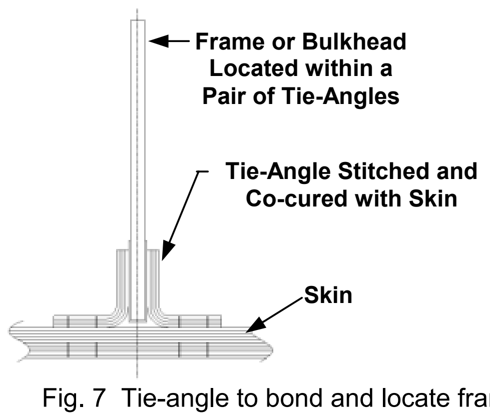

Fig. 7 Tie-angle to bond and locate frames and bulkheads

fasteners in major sub-assemblies were eliminated, parts count reduced and manufacturing streamlined.

Fittings

There are six highly loaded fittings, to which are mounted the four trusses from the transmission and the two engines. The tension fittings of the original metal fuselage were re-designed as shear fittings.

Upper Deck

The upper deck was a hand lay-up, carbon prepreg design. It was secondarily bonded to assemble it to the unitized skin-stringer-frame structure. Mid-span stiffeners and longerons along the edges are integral to the deck. In order to accommodate variability in fabrication, the deck is manufactured in two longitudinal sections. The secondary bonding reduced both fastener count and weight. Joint integrity was further assured by minimizing peel stresses with a shear-resistant design, and with bonding surfaces having the same coefficient of thermal expansion (CTE). The weight was minimized with Syncore and by tailoring the skins.

Aluminum Components

Aluminum was judiciously used for highly loaded parts with complex geometry. Metal re-distributed the loads more efficiently and simplified both the design and the manufacture of the component and the adjacent composite structures.

Manufacture of the RWSTD Center Fuselage

Overview

The key technologies that reduced the recurring manufacturing cost of the RWSTD center fuselage are schematically summarized in Figure 9. Prior to building the fuselage, computer-based simulation tools were used to optimize the design of the parts, the assembly sequence, and tooling ergonomics to insure affordability (Ref. 2).

The manufacture of the RWSTD center fuselage started by first stitching a 10-foot by 14-foot carbon fabric with longitudinal stringers and transverse frame tie-angles. The stitched preform was then drape-formed and loaded into a female mold. Finally, precured RTM frames and bulkheads, stringer mandrels, and vacuum bags were located in the mold, and the preform was VaRTM-infused to build a unitized structure requiring very few fasteners. The unitized structure was cured in an oven at 250° F.

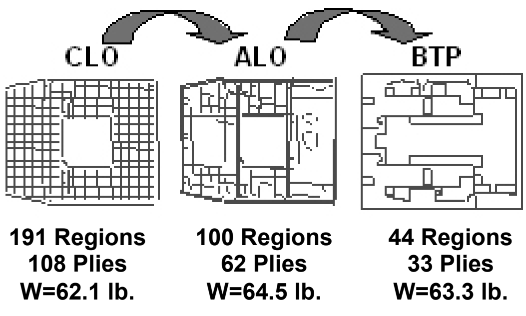

Fig. 8 Evolution of the design of the skin-stringer preform

Final assembly of the RWSTD center fuselage included bonding decks, and fastening various metal components such as the pilot's floor (a high-speed machined component), main landing gear frame, and rotor truss and engine support fittings. By using coordinated tooling holes and part-mating features, the need for expensive final assembly jigs was eliminated.

Preform Fabrication and Stitching

To manufacture of the basic skin-stringer preform, two geometry definitions were required: a contoured version to support the design of the VaRTM mold; and a flat version for cutting the flat patterns, designing the stitching frame, and programming the stitching machine. This was made possible with PACKS, Ref. 4. The flat 3D pattern is an assembly of all of the plies. This definition allowed programs for ply cutting and nesting, and for the stitching frame to be developed. The high fidelity Unigraphics® CAD models defining the geometry of the skin and stiffeners are shown in Fig. 10. The longitudinal reinforcements are stiffeners, and each transverse "reinforcement" is a pair of tie-angles to locate the frames and the bulkheads.

With the geometry of the ply stack defined, the next step was the design of the stitching frame. The frame, made of heavy-gauge aluminum extrusions, supports the basic preform plies and provides

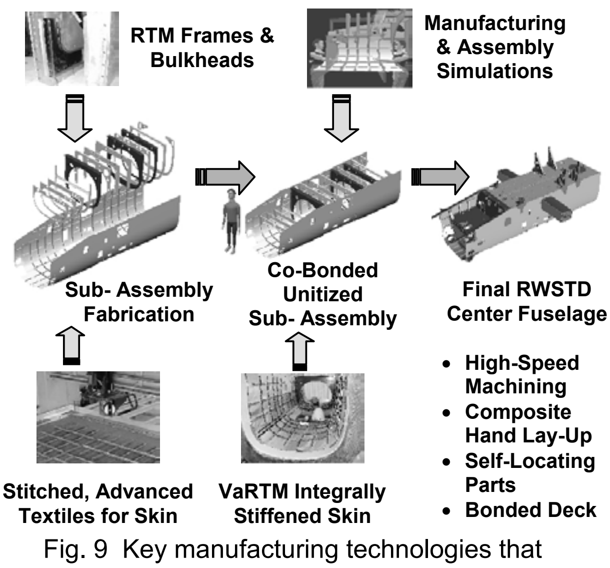

Fig. 9 Key manufacturing technologies that reduced cost

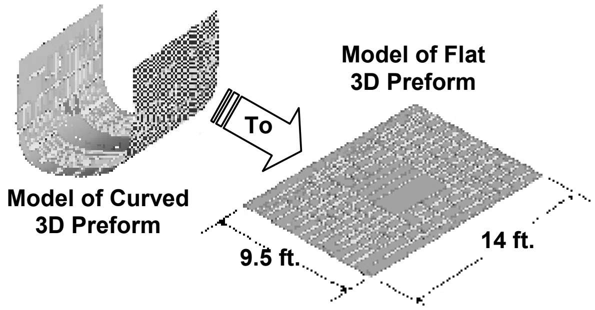

Fig. 10 CAD models of basic skin-stringer preform

indexing features for the stiffener-locating templates. The templates support individual stiffener preforms, when they are stitched to the basic preform. These templates are machined to match the contour of the varying thickness of the basic preform, the program for which was developed from the definition of the flat 3D pattern. The frame consisted of three separate sub-frames in order to increase the stiffness of the frame, and improve ease of handling and ergonomics.

After building the basic preform, stringer preforms were next cut to size and stitched using numerically controlled (N/C) machines. The stringer preforms presented a manufacturing challenge because of the multiple ply drops in their construction. An innovative nested, flat pattern was designed that incorporated variable ply thickness in the ply stack blank. Thus, final cutting, nesting, and stitching of the stiffeners were accomplished with only one set-up. The upright blades of the stiffener preforms were stitched to prevent unraveling of the edges.

The preforms for the tie-angles were made from the thinner of the two warp-knit material forms with all fibers oriented at $\pm45^o$. This fiber orientation can be readily "stretched" to the desired shape - permitting the basic preform to be drape-formed within the female mold without buckling the tie-angles.

The basic skin-stringer preform was first stitched in the stitching frame with a 2-inch pitch to stabilize the individual plies. Following which, stiffener preforms were added and located by their respective templates. Each stiffener was attached to the basic preform with two rows of stitches in each flange. The first row was stitched with the templates in place, and the second row with the templates removed to permit stitching close to the corner radius of the stiffeners. Stitching the stiffeners with and without the locating templates is shown in Fig. 11. Both stiffeners and tie-angles are visible in the lower picture of Fig. 11. Additional plies, 0.18-inch thick, were tack-stitched over the skin and flanges of the stiffeners to reinforce cutouts for sub-systems in highly stressed regions. The finished 10-foot by 14-foot skin-stringer preform is shown in Figure 12.

Ergonomic difficulties were encountered when stitching such a large basic preform. The difficulty was alleviated by designing the locating templates to be pre-assembled before installation. However, some assembly work in the middle of the preform required scaffolding for access (see Fig. 11).

In addition to the basic skin-stringer preform, the preforms of fuel cell access covers were also stitched. These covers also act as energy absorbing panels during crash-impact. The tailored stitching assures progressive and uniform crushing of the hat-stiffened bulkhead covers for efficient energy absorption. In addition to tailoring the stitches, ply tailoring reduced the weight of the covers. The final assembly of the cover was completed by stitching hat stiffeners with foam mandrels in place. The finished preform of the access cover is shown in Figure 13.

Modular RTM Tooling and Manufacture of Frames and Bulkheads

The thirteen frames and bulkheads were built with two basic molds with inserts. Each mold consisted of a stack of four chambers. The two outer chambers are the re-usable basic mold, and have built-in cavities for hot oil to circulate to heat the mold. The

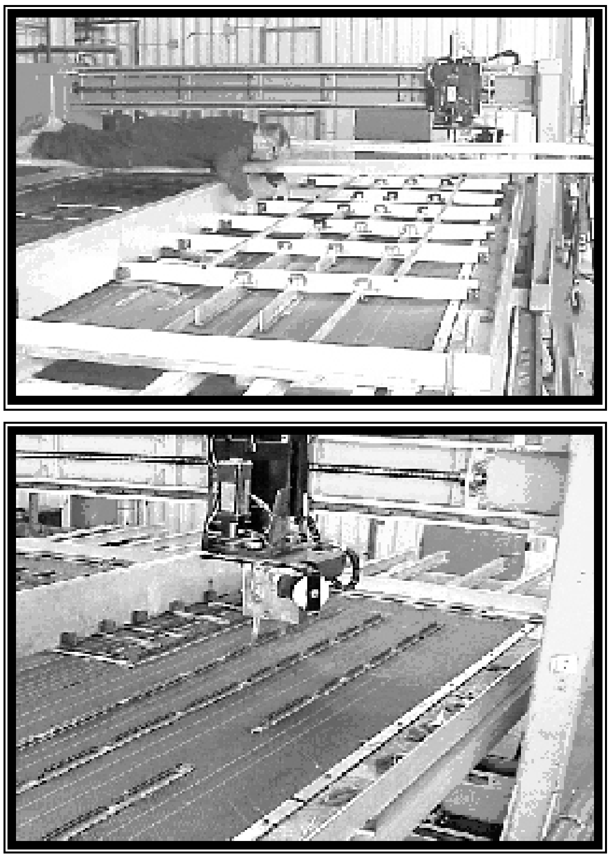

Fig. 11 Stitching stiffeners on to basic skin preform with (top) and without (bottom) locator fixtures.

inner two chambers have interchangeable sets of inserts to manufacture configuration-unique features of the different frames and bulkheads. The larger inserts included resin feed grooves around the perimeter of the part cavity to provide a radial pattern for resin flow. The basic components of the modular tool are shown in Fig. 14.

The steps in the RTM manufacture of the frames and bulkheads are given below.

- Fabricate the preform by stacking individual carbon plies and tack them with an electrostatic spray. The ply stack is then vacuum-consolidated to achieve near-net dimensions, and loaded into the mold.
- Complete assembling the mold. The mold is heated by circulating hot oil through the upper and lower chambers of the 4-stack modular mold. PR-500 resin is then injected into the two central mold cavities where the preform is located. Cure is at 350° F.
- The mold is then disassembled and the part removed. The tool was disassembled at 275ºF to prevent the part from being damaged due to the contraction of the tool if it was cooled to room temperature.
- Once de-molded, the part was hand trimmed to remove resin flash. Conical inserts incorporated in the mold provided reference points for hand drilling pilot holes for fasteners and coordinated assembly holes.

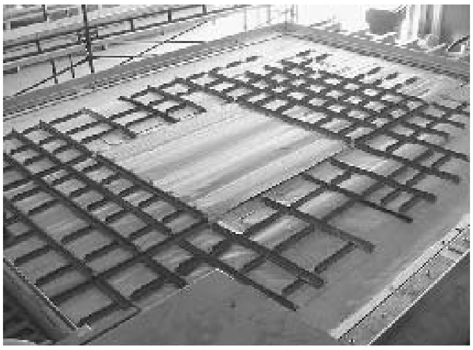

Fig. 12 Completed skin-stringer preform

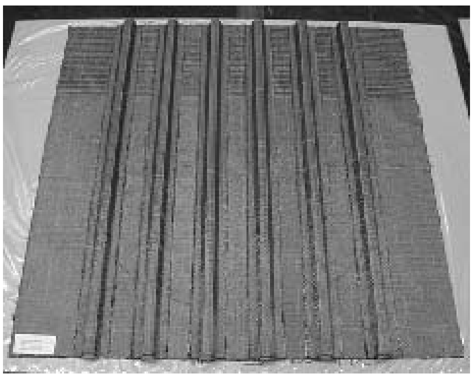

Fig. 13 Completed preform for access covers

The final tool design permitted eight different frames to be built with one modular base mold, and five heavier bulkheads with a second modular base mold.. The range of the geometries of the eight frames from a single base mold is shown in Fig. 15.

VaRTM Tooling

The specific VaRTM process used was the Seemann Composite Resin Infusion Molding Process (SCRIMP) of Seemann Composites of Gulfport, Mississippi. The tools for the VaRTM process are a main mold, mandrels, locator tools, and vacuum bags. As in all liquid molding processes, the tooling is designed for the resin to flow uniformly and distribute evenly across the preform. The unique geometry of the preform dictates the number of mandrels and locator tools required to assure geometric and dimensional accuracy. The preform of the RWSTD fuselage was infused in a deeply curved female main mold. The main mold had

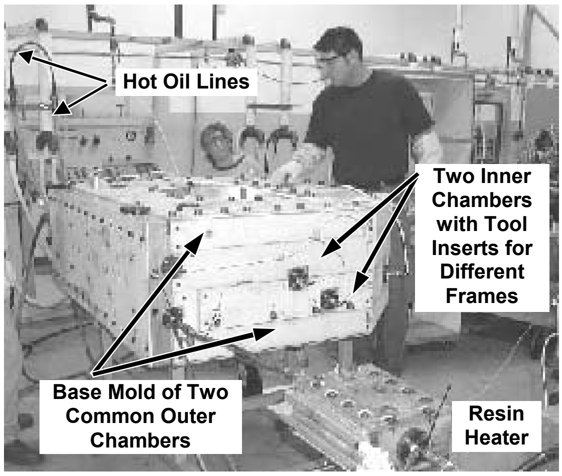

Fig. 14 Assembly of modular RTM tool

Fig. 15 Eight different frames built with one base mold

circumferential resin-feed grooves and resin supply ports for all surfaces of the preform to be evenly infused. The stringers, tie-angles and longerons of the preform were supported by mandrels, precured frames and bulkheads were positioned with locator tools, and vacuum bags sealed the entire assembly. To insure proper wet-out of the preform and reduce the time for infusion, a resin distribution medium on the mold surface, a proprietary flow-path material in the reusable vacuum bags and vacuum ports were strategically located.

The female mold was 15 feet long and was built with tackified carbon tooling cloth using a male tool. Reinforcement plies were added around resin-feed areas. The contour of the inside surface was machined to within ±0.010 inch of the loft surface. The cutout in the middle of the mold for the ammunition door provided access for operations inside the mold. The finished carbon-epoxy mold is shown in Fig. 16. The precured frames were accurately located with jigs on the top surfaces, and with clips on longeron mandrels for the bottom surfaces. The carbon-epoxy jigs had the same low CTE of the composite mold.

To build accurate, reusable vacuum bags, N/C machined master tools were used to lay up and cure the 0.10 inch thick silicone rubber bags. The finished master tools were 2% oversize to compensate for the large shrinkage of silicone rubber during its cure. This oversize was needed despite the fact that the aluminum master tool expands at the 250º F curing temperature. A silicone vacuum bag was required for each of the 14 bays of the structure. The two bays with cutouts in the middle of the mold required two bags per bay.

An innovative approach was taken to design the stringer mandrels. Back-to-back angles with machined recesses were used to create a near-net molded stiffener that required little secondary trimming after cure. Spring clips secured the lightweight mandrels to the stitched preform stiffeners and prevented the mandrels on the vertical walls of the mold from sagging out of position, prior to installing the bag.

VaRTM Infusion Process

The tooling for the VaRTM process was designed for the resin to infuse the stitched skin-stringer preform and simultaneously cobond the precured RTM frames and bulkheads. The sequence of operations to build the unitized sub-assembly of the RWSTD fuselage is shown in Figure 17. The illustrations in the figures are part of the 3D CAD models of the manufacturing simulation tools.

The mold preparation and the loading of the drape-formed preform are shown in Steps 1 to 3 of Fig. 17. The preparation of the frame is also shown. It

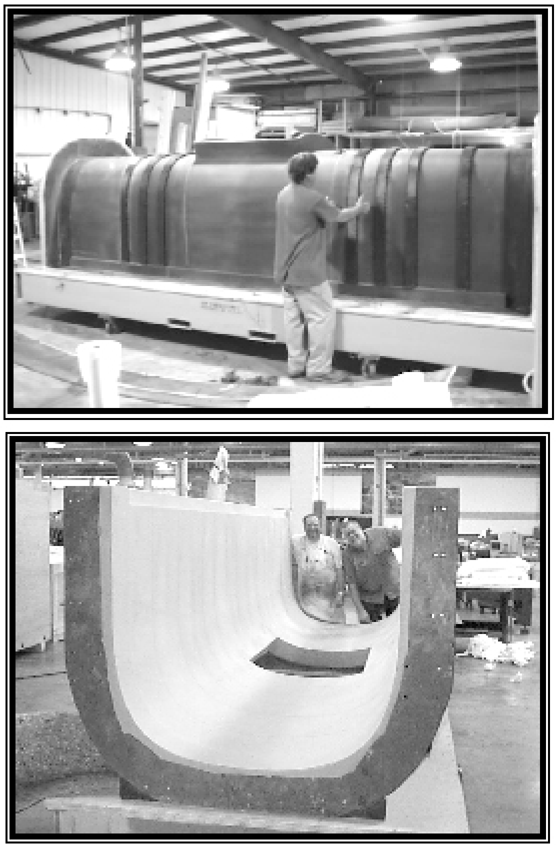

Fig. 16 Main VaRTM mold during fabrication (top) and after cure and machining of the inner surface (bottom)

included sanding to prepare bonding surfaces, and installing rubber wedges to simplify vacuum bag installation.

The loading of the precured frames, bulkheads and the stringer mandrels are shown in Steps 4 and 5. The upper frame locator tools were loaded in Step 6, and were pinned to the shoulder of the mold. The locator jig prevented the preform and frames from shifting out of position when the vacuum bags were later installed.

The final assembly of the mold is illustrated in Steps 7 to 9. The rubber wedges that intensified the pressure in the bond area between the frame and the stitched attachment angles were installed at Step 7.. The 16 different vacuum bags were loaded and seated (Step 8). A double row of sealant was used along the perimeter of each bag to insure a vacuum. The bags were sealed to the top shoulder of the mold, the precured frames, and to each other. The bagging operation was relatively quick, since the reusable silicone bags had been accurately made to fit the shape of the preform, frames and tools.

Prior to infusion, the bagged preform and frame assembly was dried at 150º F under vacuum for 12 hours. The SI-ZG-5A resin was advanced to B-Stage at 150º F to optimize its viscosity.

Infusion was completed in less than 10 minutes; but, the resin was re-circulated for 2 more hours to flush out any trapped air and seal any minor leaks in the vacuum bags. With full vacuum applied, the infused structure was cured at 250º F for 6 hours in an oven.

The finished unitized sub-assembly is shown in Fig 18. Laminate quality was very good, with fiber volumes averaging at 55% and very low void content.

Final Assembly

The order in which the components were assembled was the machined bulkhead for the landing gear, the composite deck and the partially assembled composite wing spars. After the deck was installed, the composite sub-assembly was essentially a self-supporting structure that didn't require expensive support and locating fixtures. A determinate approach was used for the final assembly which reduced the recurring labor cost, improved access for drilling, and eliminated traditional part locator and drill jigs.

Achieved Metrics and Exit Criteria

For RWSTD, weight and recurring manufacturing labor reductions were the critical technical performance criteria. The metrics, shown in Table 2, were a 15% weight reduction (to 298.7 lb.) and 25% reduction in P-1 manufacturing labor hours (to 6,454 hours), compared to a 1994 Technology Baseline. These metrics were monitored throughout the program, using analysis predictions early in the program and ultimately verifying these predictions as parts were built, assembled and weighed. Additional related metrics to measure success in reducing manufacturing cost were reduction in parts and fastener counts, and the as-manufactured dimensional accuracy. Finally, to determine the improvement in engineering productivity of IPT using IPPD tools, the engineering development hours were also measured and compared to a baseline development program.

Weight

The final weight of the RWSTD demonstration article is of 306.0, which exceeded the exit criteria of the program by 7.3 lb. and resulted in a 13% reduction in weight. In analyzing the cause of the increase in weight, it was found that the laminates on the VaRTM parts were 6% thicker than predicted and

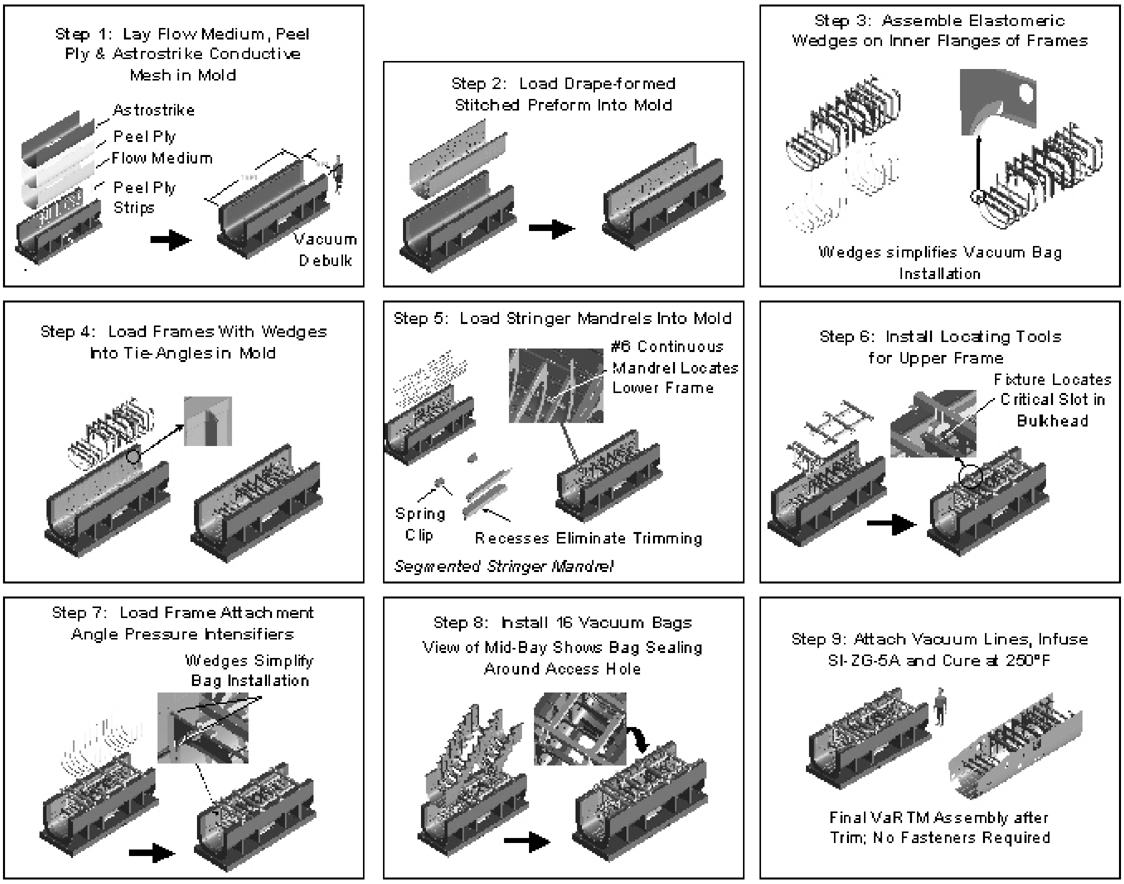

Fig. 17 The VaRTM manufacturing plan

that a significant amount of excess resin resided where tool fit-up was inaccurate. Parts made by all other manufacturing processes correlated well with predictions.

Recurring Manufacturing Labor-Hours. The P-1 manufacturing labor hours for the RWSTD fuselage was 4,426, or a reduction in manufacturing labor hours of 49%. A breakdown of the measured manufacture touch labor hours is summarized in Fig. 19. The cost for final assembly was only 24%, compared 38% for the 1994 Technology Baseline, and over 50% for the existing metal fuselage (of 1970s design). The low cost of the final assembly reflects the success in designing a unitized sub-assembly. Final assembly efficiencies are attributable to the accuracy of the self-locating parts and the assembly sequence plans that evolved from the assembly simulations.

Fastener Count. Reducing fastener and parts counts was critical to achieving the affordability goals of the program. The RWSTD advanced design required only 45% of the fasteners needed to assemble the 1994 Technology Baseline. In comparison to the existing 1974 metal fuselage, fasteners were reduced from 12,100 to 2,900. The significant reduction in fasteners was primarily due to the stitching process and the VaRTM unitized structure. Most of the fasteners used on the RWSTD fuselage were for assembling metal components and removable access covers.

Parts Count. The reduction in parts count was 22% in comparison to the 1994 Technology Baseline. The majority of the 132 parts were those retained as, and redesigned from, metal. It is interesting to note that the average composite part was significantly larger than the average metal part. The composite parts weighed on an average four pounds, and the metal parts on an average weighed only one pound.

Dimensional Tolerance and Accuracy

Since the RWSTD utilized RTM process and the relatively new manufacturing VaRTM process to fabricate a large unitized structure, the capability of the liquid-molding processes to produce dimensionally accurate parts was largely unknown. To capture this process capability, dimensional tolerances were established on critical mating features of the individual parts that would support a goal of shim-less final assembly. Completed parts were inspected to verify compliance. In general, tolerances were set tighter than would be needed in production. Similarly, laminate quality requirements were stringent to meet weight requirements and to match the laminate quality of the small coupons tested for the material allowables.

RTM. The dimensional inspection results of the composite frames and bulkheads built using the RTM process are summarized in Table 3. In general, the dimensional accuracy of the parts was excellent. Part accuracy was a direct result of the accurately machined cavity tools used to mold the parts. Compensation factors for thermal expansion were correctly applied to the machining of the aluminum molds; however, resin cure shrinkage factors that affect flange “spring-in” were not correctly compensated. Based on the RTM risk reduction tests, a 1.5° correction factor was used for the full-scale parts, but due to changes in the lay-up and geometry of the flanges, the spring-in of the full-scale frames was significantly less than that of the risk reduction parts.

VaRTM. Dimensional tolerance for the VaRTM unitized sub-assembly were generally looser than that for the RTM parts. At critical assembly interfaces, such as frames, hard tool locators were used to position frames accurately. Similarly, critical stringers that interface with the forward and aft sections of the AH-64 fuselage required mandrels with hard locating features on the main mold. Other less critical part features such as intermediate stringers had positional requirements of ±0.090 inch that were controlled by the molded-in mandrel cavities of the vacuum bag. The results of the dimensional inspection of the 22 critical end-bay stringers are shown in Table 4. Approximately half of the stringers were located outside the tolerance. Major contributors to the inaccuracy were resin

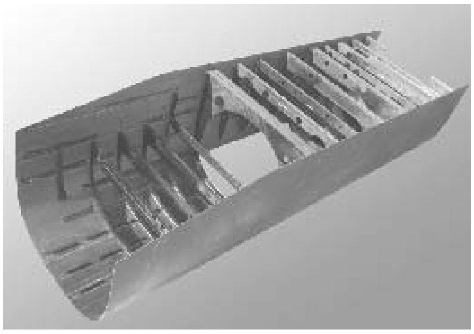

Fig. 18 The VaRTM-infused unitized sub-assembly

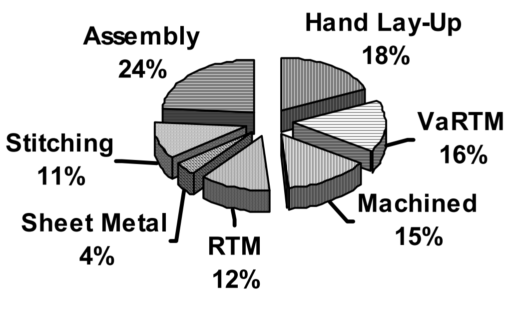

Fig. 19 Summary of measured manufacturing labor hours

shrinkage during cure and improper seating of the back-to-back stringer mandrels on the stitched preform.

Table 3 Dimensional Accuracy of RTM Frames

Requirements	Results
Profile Tolerance within ±0.005 inch	Part features controlled by mold were within tolerance
	Hand trimmed features were out of tolerance
Flange Angle Tolerance within ±0.25°	"C" Flanges ±0.75° out of tolerance*
	"T" Flanges ±1.25° out of tolerance*

Table 4 Dimensional Accuracy of VaRTM Stringers

Requirements	Results
Stringer Location Tolerance within ±0.030 inch	Locations ranged from 0.004" to 0.0709" from the nominal
	10 locations were 0.001" to 0.0409" out of tolerance
Stringer angularity tolerance within ±1.5°	3 stringers ranged from 0.1° to 1.73° out of tolerance
	"T" Flanges ±1.25° out of tolerance*

The results of the dimensional inspection of the locations of the 13 frames and bulkheads after cobonding with the VaRTM process, indicate that butt-lines and waterlines were within tolerance. However, station locations were significantly out of tolerance over the 14-foot length of the carbon-epoxy structure. For three of the frames, the main cause was due to inaccurate installation of the lower locator tools. For the remaining frames; resin shrinkage during cure was the only plausible explanation for the 0.3 inch short dimension between the forward and aft frames. Only one mid-frame at Sta. 176 was within tolerance, and the remaining frame positions contracted relative to that reference during the cure.

Laminate Quality

The final manufacturing metric was laminate quality. The thickness and fiber volumes of the RTM and VaRTM laminates are summarized in Table 5. Fiber volume fractions matched expectations for both processes; however, laminate per ply thickness for the VaRTM parts averaged 6% thicker than the test coupons. Void content was less than 0.01% in the RTM and VaRTM laminates, which is typical of liquid molded processes.

Non-Recurring Engineering Labor Hours

The last performance metric measured was the reduction in non-recurring engineering development hours to complete the design of the RWSTD center fuselage as compared to previous structural development programs. This metric essentially measured the success of the IPT in implementing and applying the suite of DMAPS IPPD tools. The specific goal for this metric was to reduce non-recurring engineering labor hours (in terms of hours per pound of structure) by at least 40% compared to the engineering manufacturing development (EMD) Phase of the V-22 Program. The V-22 structural design activity represented an appropriate baseline since it was a relatively recent program where extensive CAD systems and tools were used.

The reduction in non-recurring engineering development hours was 41% compared to the goal of 40%. The significance of this reduction, in terms of engineering hours per pound, is given in Table 6. The RWSTD fuselage is compared with those of the fore body of Boeing's X-32B (JSF) aircraft, and the baseline V-22 fuselage for EMD phase. In the past, development hours have always increased with increasing composite content. The RWSTD labor metric is 20% higher than that of the JSF fore body; however the composites content in the RWSTD is 74% compared to the JSF's 25%. Thus, the approach, the methodology and the tools used to develop the RWSTD fuselage clearly were effective in significantly reducing engineering development time and labor hours.

Table 5 Laminate Quality

	RTM Frames	VaRTM Skin and Stringers
Thickness	Nominal ±0.002 inch	0.005 to 0.010 inch Oversize
Fiber Volume	53% by Design	55%

Manufacturing Process Touch Labor Hours Normalized by Weight

Five Manufacturing processes were used on the RWSTD center fuselage: machining, sheet metal, hand lay-up, RTM and VaRTM. The percentage cost of each process, together with stitching and assembly, are shown in Fig. 19. Eliminating stitching and assembly, the percentage of recurring manufacturing labor hours, the percentage of weight of the structures built by each of the processes and the respective manufacturing labor hours per pound are shown in Fig. 20. It is evident from the figure that advanced liquid molding processes can be at least as cost effective, if not more, than metal processes in manufacturing large composite aerospace structures.

Table 6 Engineering Labor Hours Per Pound of Structure

Program	Percentage of Composite by Weight	Non-Recurring Engineering Hours per Pound of Structure
Boeing X-32B (JSF) Forebody	25	94.2
V-22 EMD Baseline Fuselage	45	207.2
RWSTD Apache Fuselage	74	113.0

Summary and Conclusions

- The RWSTD program has demonstrated that composite technology can make the manufacture of large, complex geometry of a legacy skin-stringer-frame fuselage structures affordable. The technology can readily scale up to larger structures, especially if the new designs incorporate larger spacing between bays.
- The ”define” cycle-time for a composite structure of this complexity and size was reduced dramatically by employing an IPT, the DMAPS approach and knowledge-based PACKS composite design tool.
- The goal to reduce the cost of the P-1 unit by 25% was successfully demonstrated on the program. The weight reduction demonstrated was 13%, slightly lower than the goal of 15%.
- Stitching technology and parts consolidation eliminated 75% of the fasteners used in the legacy metal fuselage, and were key to achieving the exit criteria.
- The flat stitched skin-stringer preform of the RWSTD fuselage was successfully drape-formed to the deeply curved region of the AH-64 loft. However, applying stitching methods to structures with compound curvature will require advances in curved stitching technology.
- RTM with modular tooling permitted the economic manufacture of composite frames with the precision of machining metal for a prototype program like RWSTD.
- The cobonding technology of VaRTM enabled an aggressive approach for assembling in the mold, which eliminated many secondary assembly and riveting operations. With additional advances in stitching, textile, and resin technology, liquid-molding processes will likely supplant the conventional prepreg lay-up and autoclave process.

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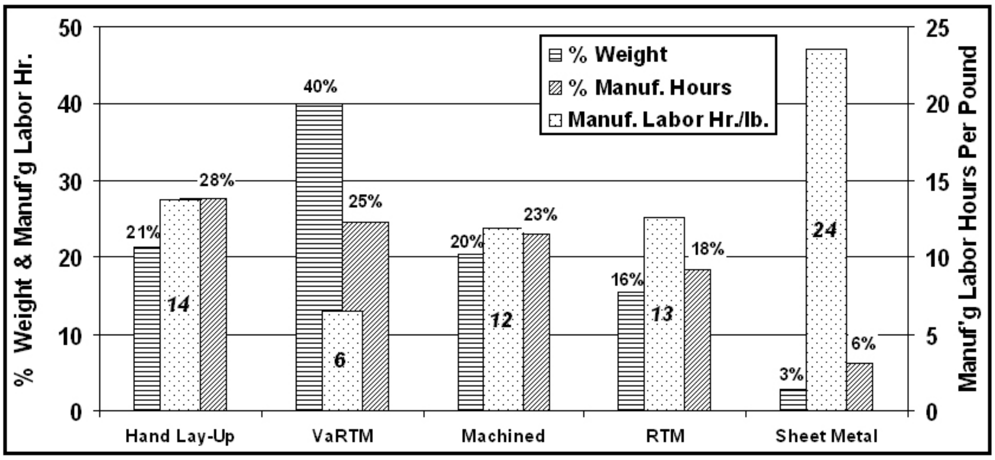

Fig. 20 The manufacturing hours and weight of structure built by the five manufacturing processes