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ADVANCED TECHNOLOGY COMMERCIAL FUSELAGE STRUCTURE[1]

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ABSTRACT

Boeing's program for Advanced Technology Composite Aircraft Structure (ATCAS) has focused on the manufacturing and performance issues associated with a wide body commercial transport fuselage. The primary goal of ATCAS is to demonstrate cost and weight savings over a 1995 aluminum benchmark. A 31 foot section of fuselage directly behind the wing to body intersection was selected for study purposes. This paper will summarize ATCAS contract plans and review progress to date.

The six year ATCAS program will study technical issues for crown, side, and keel areas of the fuselage. All structural details in these areas will be included in design studies that incorporate a design build team (DBT) approach. Manufacturing technologies will be developed for concepts deemed by the DBT to have the greatest potential for cost and weight savings. Assembly issues for large, stiff, quadrant panels will receive special attention. Supporting technologies and mechanical tests will concentrate on the major issues identified for fuselage. These include damage tolerance, pressure containment, splices, load redistribution, post-buckled structure, and durability/life.

Progress to date includes DBT selection of baseline fuselage concepts; cost and weight comparisons for crown panel designs; initial panel fabrication for manufacturing and structural mechanics research; and toughened material studies related to keel panels. Initial ATCAS studies have shown that NASA's Advanced Composite Technology program goals for cost and weight savings are attainable for composite fuselage.

INTRODUCTION

Technology advancements are needed to insure that the United States retains a majority share of the world market in transport aircraft. Composites have shown the potential to achieve improved performance (e.g., increased fatigue and corrosion resistance) and reduced weight relative to aluminum aircraft structures. However, higher costs associated with past composite structures remain an economic barrier to increased applications. A balance between cost and weight efficiency appears possible by integrating composite design, manufacturing, material, and structures technologies.

The application of affordable composite technology to transport fuselage is addressed in Boeing's program entitled Advanced Technology Composite Aircraft Structure (ATCAS). This program started on May 12, 1989. Assuming that all phases and options are funded, ATCAS is scheduled to be completed by the middle of 1995. The main ATCAS objective is to develop an integrated technology and demonstrate a confidence level that permits cost- and weight-effective use of advanced composite materials in future primary aircraft structures with the emphasis on pressurized fuselages.

An aft fuselage section directly behind the wing to body intersection is used for technology development and verification purposes in ATCAS. This section of fuselage, referred to as section 46, has many design details and associated technology issues that pose a staunch test of advancements in

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composite primary structures. The design envelope (i.e., size, loads, and configuration constraints) chosen by ATCAS is based on preliminary data for section 46 of the 767-X (a current development program for an airplane 80% the size of a 747). The 767-X has a 240 in. diameter aluminum fuselage. The parallel efforts of 767-X and ATCAS provides an opportunity to completely evaluate cost and [redacted]mposites in the 1995 timeframe.

Keel, side, and crown areas of section 46 are being considered in the ATCAS program. Some manufacturing cost issues for this fuselage section are shown in Figure 1. Although many issues are common to the entire section, each area has unique problems that must be solved in order to achieve low costs. The complexity of design details such as window cutouts and section splices result in significant cost centers. Therefore, they are included in ATCAS studies to insure that overall low-cost composite technologies are adequately demonstrated. In order to save costs as compared to metals, the relatively high price of composite materials must be countered by innovative composite fabrication and assembly processes that minimize labor costs.

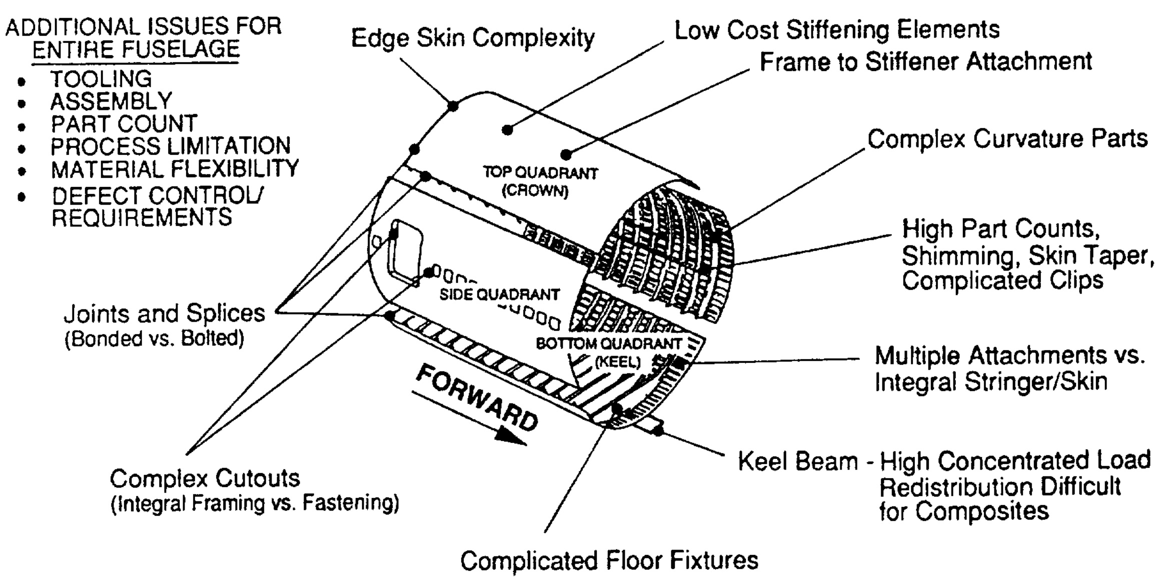

Figure 1: Cost Drivers for a Composite Fuselage

Many of the important composite structural issues, shown in Figure 2, are also unique to individual areas of the fuselage. Design of the crown is driven by tension loading. The side area is dominated by shear and pressure load redistribution around door and window cutouts. Keel design is driven by major load redistribution from the keel beam and combined loads dominated by axial compression.

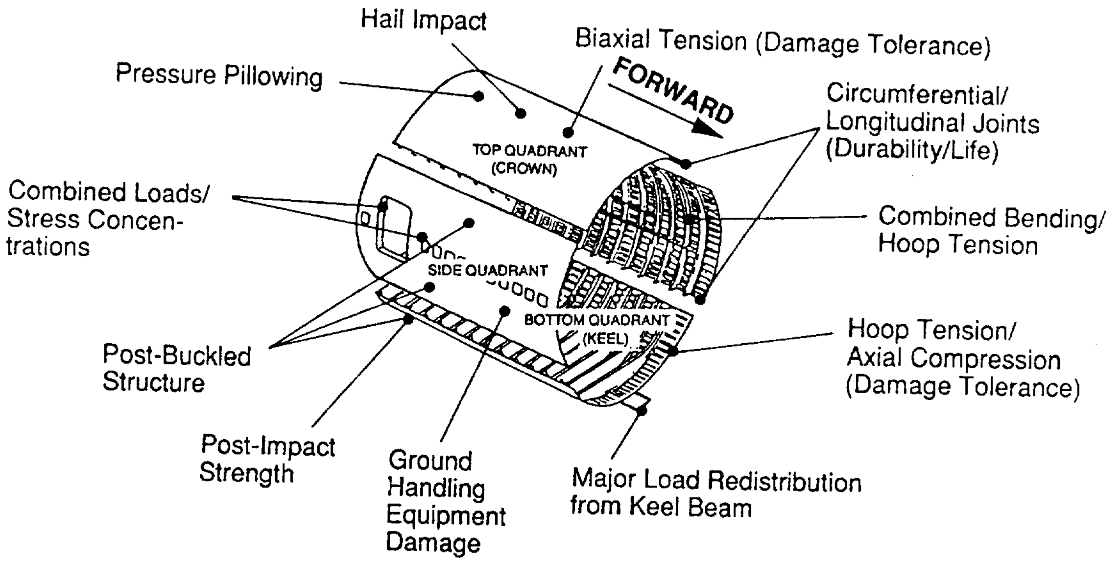

Figure 2: Structural Design Drivers for a Composite Fuselage

The remainder of this paper is broken into three main sections that overview the ATCAS program. The first describes the design build team approach. Baseline fuselage concepts and associated technical issues are described in the second section. Plans and progress to develop concepts and solve technical issues are presented in the final section.

DESIGN BUILD TEAM APPROACH

The greatest potential for saving cost and weight occurs in early phases of product development. Once the structural configuration is set, attempts to reduce weight or enhance manufacturing efficiency are traded against added costs associated with design changes. Past Boeing studies, indicating strong interactions between design details and manufacturing costs, led to a decision to consider assembled structure early in the ATCAS design cycle. The approach used for this effort is based on a design build team (DBT). The initial goal of the DBT is to identify composite design and manufacturing concepts that have a strong potential for cost and weight savings as compared to 1995 metals technology. An accurate estimate of the potential for cost and weight savings with a composite concept is established prior to the commitment for solving major technical issues.

The ATCAS DBT approach was derived by team members representing manufacturing, structural design, structural mechanics, materials, quality control, and cost analysis. As a result, each team member was given a sense of ownership in the ATCAS program. Early efforts revealed that the combined inputs from different disciplines was critical to identifying concepts with a potential for both cost and weight savings. Initial activities also indicated that the majority of work performed in support of a DBT occurs outside the group meetings used for coordination and review purposes.

Early developments by the ATCAS DBT prompted a need for an efficient method of studying candidate fuselage design concepts and manufacturing processes. Initially, 30 candidate fuselage panel concepts were produced by design personnel. The number of concepts was increased from 30 to 159 during subsequent brainstorming sessions with the full DBT. Schedules would not allow cost and weight evaluations of all concepts. Instead, concepts were classified into the eight design families (see Figure 3) having common manufacturing characteristics. This allowed a more viable DBT approach in which a reduced number of concepts, representing chosen families, are evaluated for cost and weight efficiency. After identifying the best family for a given application, the cost and weight relationships of variables within that family are analyzed in greater detail.

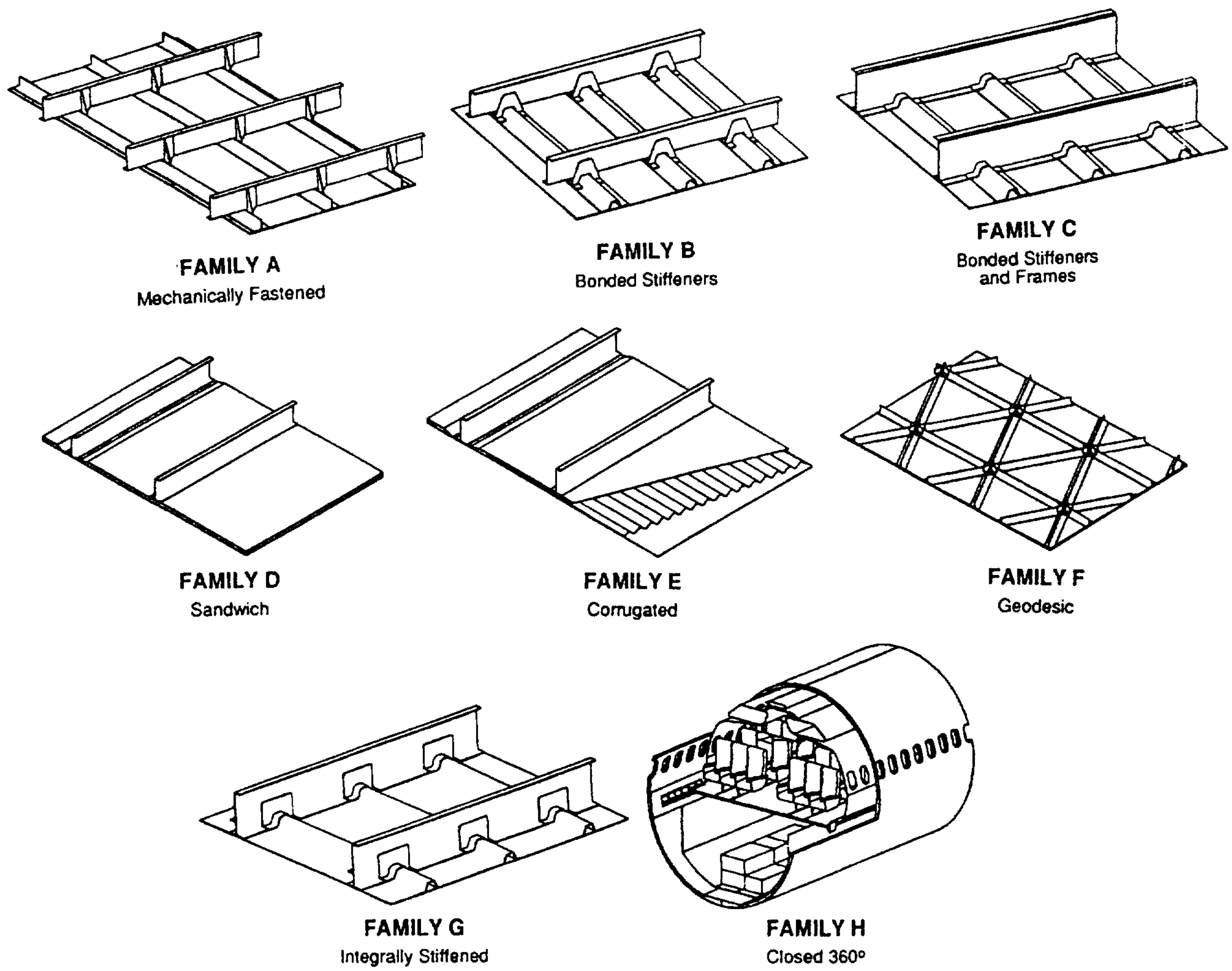

Figure 3. Representative Concepts From ATCAS Design Families.

Three steps are used by the ATCAS DBT to select, evaluate, and optimize fuselage concepts. The starting point is selection of baseline concepts as those design and manufacturing ideas having an apparent potential for cost and weight savings, combined with an acceptable risk. Technology issues are also identified during this phase of design, helping to focus early efforts in manufacturing, structural mechanics, and materials development. In the second step, referred to as global optimization, cost and weight savings are evaluated by performing detailed studies for the baseline and a limited number of alternative concepts. Global optimization effectively integrates manufacturing data into the design evaluation process. The final step, called local optimization, attacks cost centers and major technology barriers established during the first two design steps.

Figure 4 shows a flow diagram summarizing the global/local design optimization process. The cost estimating procedure for this effort uses detailed designs and fabrication/assembly plans. This facilitates cost and weight trades which consider enough details to select a cost-effective concept for further study. The ATCAS program is considering new material forms and manufacturing processes. Lack of sufficient data for these emerging technologies can reduce the accuracy of structural performance and cost predictions made during global optimization. Any uncertainties are noted and can influence the decisions made in this design step; however, the risk in selecting new technologies is minimized during local optimization which allows sufficient time to perform manufacturing trials, generate data bases, and complete more thorough analysis. Local design optimization addresses the critical cost centers, technology issues, and structural performance details. The goal of this DBT step is to minimize cost and weight, while insuring structural integrity.

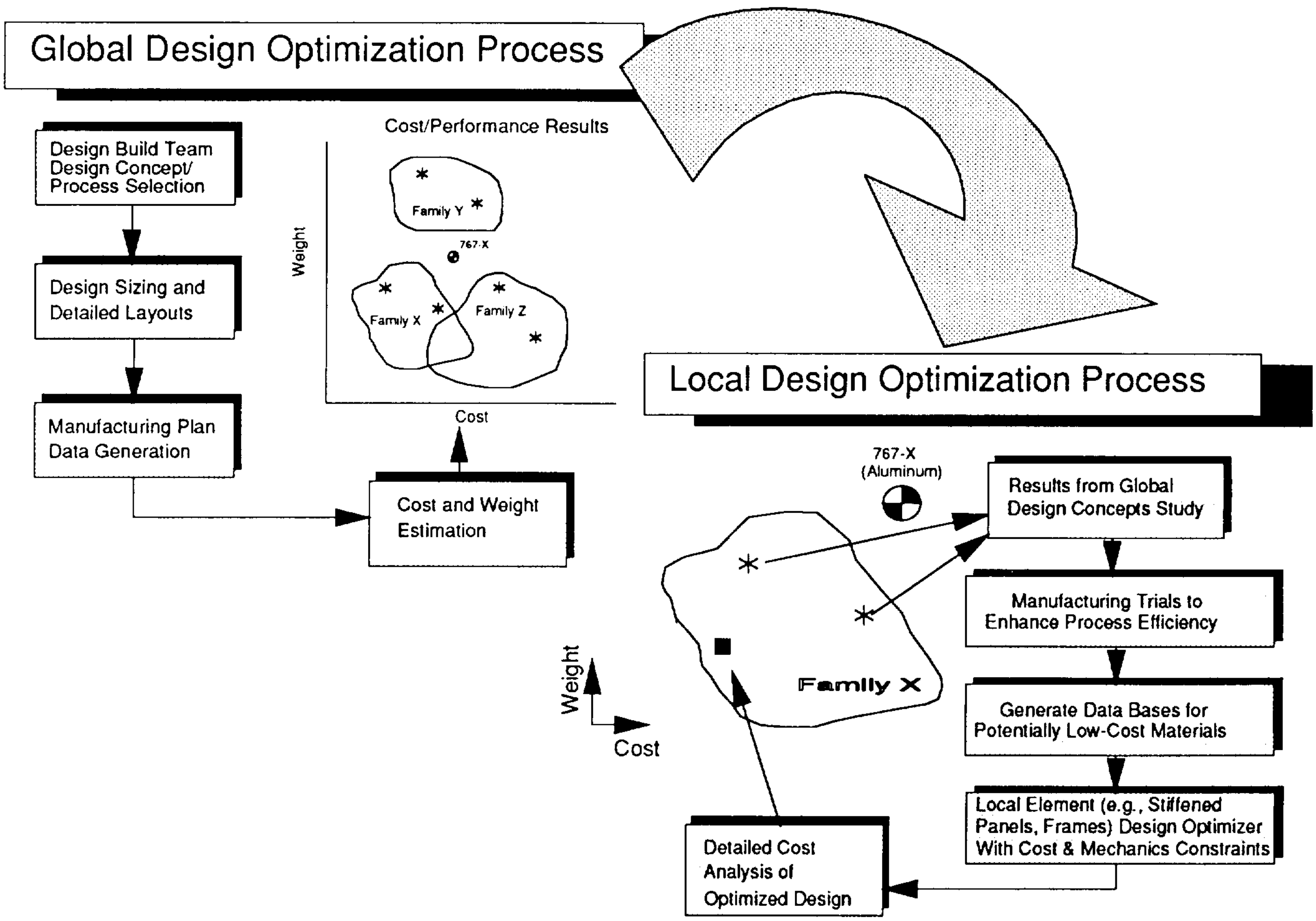

Figure 4. Global/Local Cost and Weight Optimization

BASELINE CONCEPTS

Baseline concepts have been selected for all areas of the aft fuselage section under study in ATCAS. The DBT selection rationale included several considerations. Critical manufacturing and performance issues were considered in selecting a design family that is compatible with structural details such as doors and the keel beam splice. Baseline manufacturing processes were selected to maintain cost efficiency with design details such as skin thickness tapers and curved frame geometries. Since the scheduled completion date for crown global optimization coincided with baseline concept selection for the entire fuselage section, results from the former were used as an indicator of composite cost centers. The more detailed crown studies also helped to identify promising fabrication processes for skin, stiffener, and frame geometries. Finally, the only concepts considered were those judged to have a strong potential for large fuselage subcomponent manufacturing and test demonstrations by 1995.

Quadrant Panel Definitions

A quadrant manufacturing approach was selected for baseline panels. The four quadrant segments defined for the baseline fuselage section are shown in Figure 5. The quadrant concept is intended to reduce manufacturing costs in two ways. First, fuselage section assembly costs are lower than those of the metals benchmark due to a reduced number of longitudinal panel splices. Second, the quadrant concept is compatible with an advanced tow placement batch method for processing skin panels. As shown in Reference 1, crown trade studies projected this method of skin layup to be cost effective.

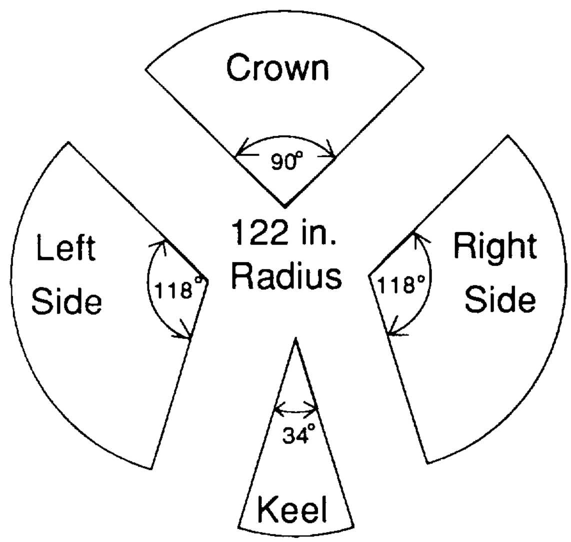

Figure 5. Exploded Circumferential View of Fuselage Quadrants. Note That Each Quadrant Panel is 30 ft. Long.

Differing arc lengths were chosen for each quadrant to accommodate the load conditions and specific design details for each area of the fuselage. Another goal was to select quadrants that minimize material waste of the batch process for advanced tow placing skins. The crown and keel quadrants were chosen as 90° and 34° segments, respectively. As shown in Figure 5, both crown and keel quadrants were symmetric about a vertical centerline to promote compatable skin gages on the right and left panel edges. The selection of a relatively small keel arc length was due to a cargo door location. Both side quadrants were large 118° segments, and include the cargo door, passenger doors, and window belt.

Figure 6 illustrates the number of manufacturing segments produced in a batch process for each fuselage quadrant. Crown and keel batch processes yield four and ten panels, respectively. Each crown or keel batch consists of uncured skin panels that are cut at the intersection of right and left edges. The side panel skin layup process required that both right and left sides be tow placed in the same batch. Each side panel skin design will have top and bottom edge layups that are compatible with the corresponding edge on the opposite side. For example, right top and left top panel edges will consist of the same thickness tailoring and layups that differ only in the sign of angle plies.

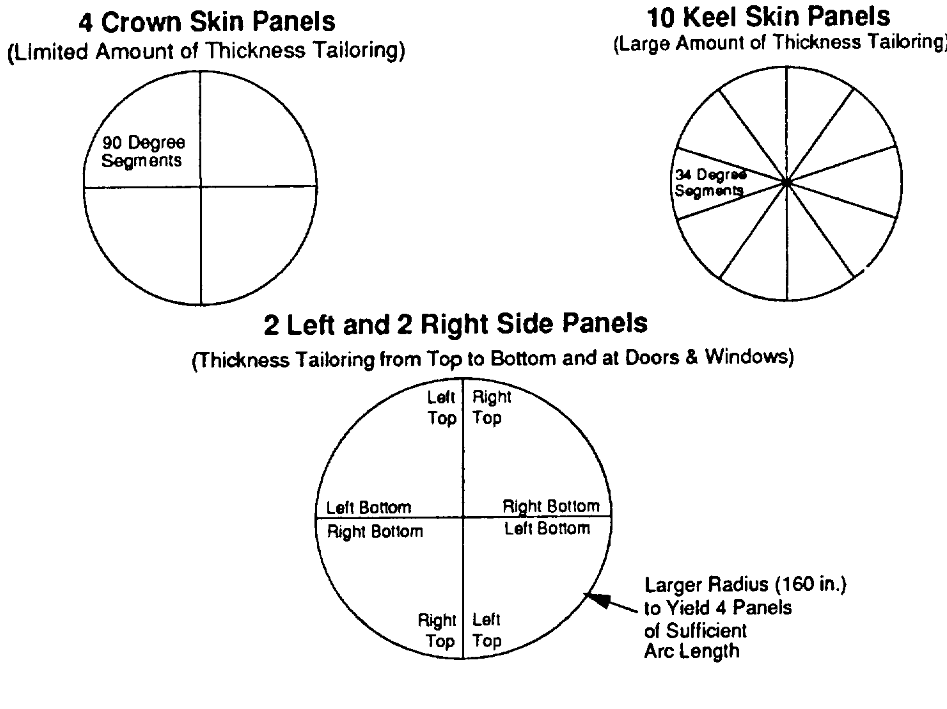

Figure 6. Cicumferential View of Tow Placed Manufacturing Segments.

Figure 7 shows the automated tow placement work.station for baseline skin panel manufacturing plans. Crown and side panel mandrals are illustrated, with the latter having a larger radius to accommodate four panels per wind. Note that both Figures 6 and 7 idealize tow placement mandrels as circular cylinders. Actual mandrel shape will accommodate design details. For example, a joggle at the edges of individual quadrant panels will be needed to allow for the geometry of longitudinal splices and cutting waste.

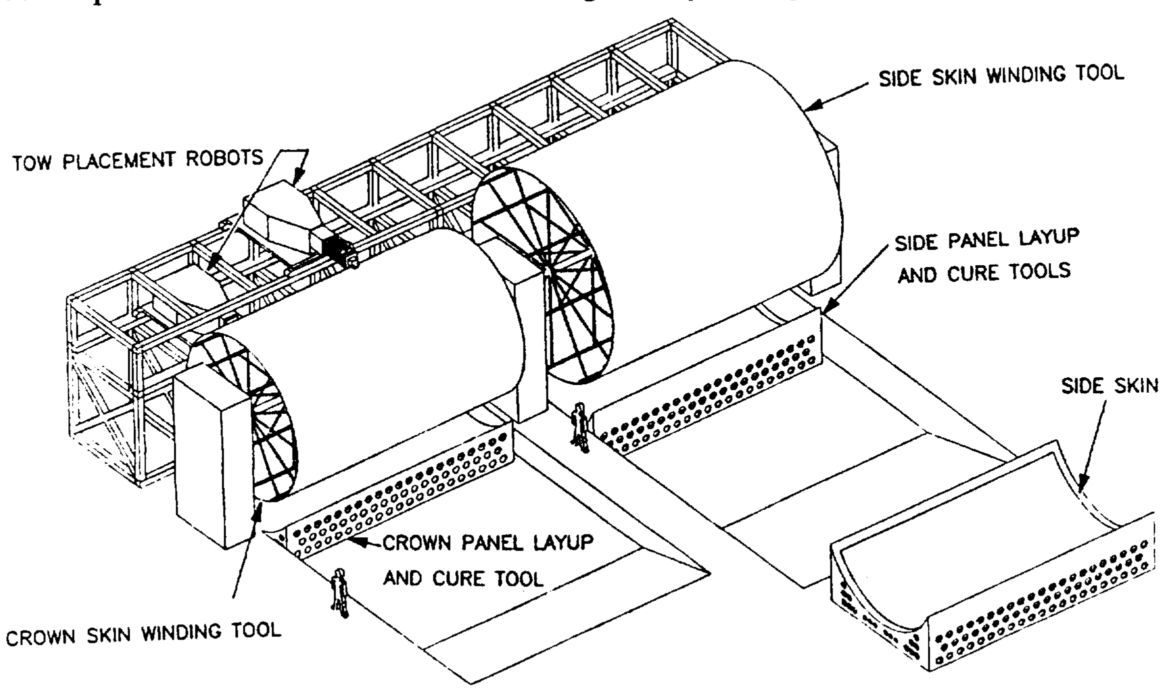

Figure 7. Automated Tow Placement Work Station.

Design Concept and Element Process Descriptions

A full factory flow from element fabrication through final assembly was envisioned to support baseline concept selection. Individual element processes are summarized in the following discussion. Mechanically fastened joints were chosen for splicing quadrants and section joining during final assembly. Additional features of the manufacturing processes appear in Reference 2.

Crown: Detailed cost and weight estimates from global optimization substantiated the baseline choice for the crown quadrant. Results from this effort are summarized later in this paper. A design concept from Family C (skin/stringer/frame with bonded stringers and frames) was chosen as the crown baseline. Figure 8 illustrates a representative area of the crown baseline quadrant. Frames are mouse-holed to avoid a complex bonding detail with the hat shaped stringers.

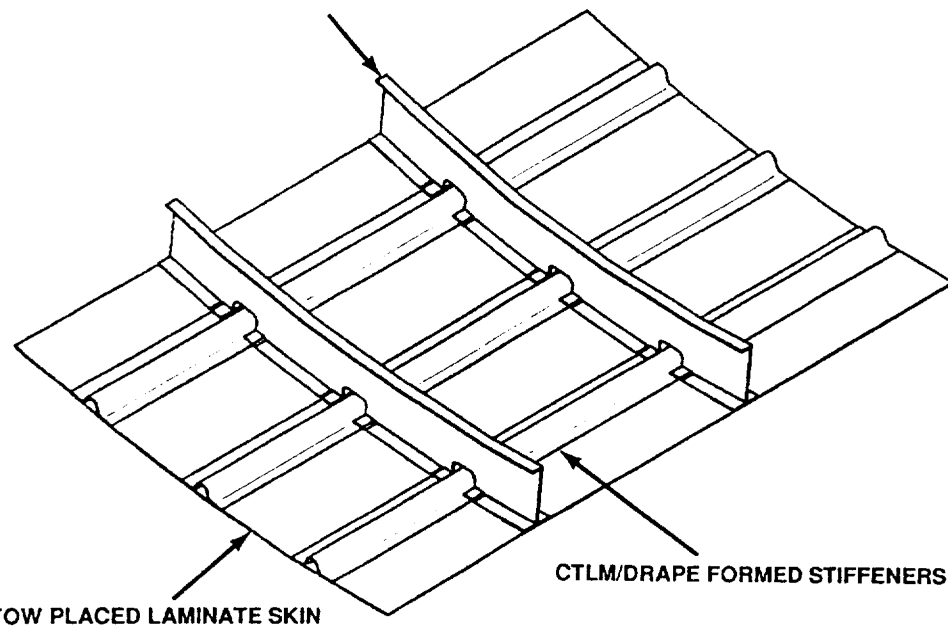

Figure 8: Crown Baseline Design Concept and Fabrication Processes.

Skin panels constitute the bulk of crown quadrant weight. Computer automated advanced tow placement was selected to layup the skins. The previous subsection gave some additional details on manufacturing multiple skin panels in a batch process.

Additional crown baseline elements include hat stiffeners and J frames. A contoured tape lamination machine (CTLM), followed by a drape forming process was selected to layup and shape the hat stiffeners. Textile preforms in a J-shape and a resin transfer molding (RTM) process were chosen to form curved frames. The frames will have sufficient thickness to account for stress concentrations at the mouse-holes. Finally, the autoclave fabrication of full crown quadrant segments (≈ 192 in. by 374 in.) was envisioned as wet skin and stiffeners, cobonded with frames.

Window Belt (Side): A variation of design concepts from Family C (skin/stringer/frame with bonded stringers and frames) was chosen as the side panel baseline. The variation includes door and window design details. Figure 9 illustrates the window belt area of the side panel baseline. A skin/stringer/frame design family was chosen to facilitate design details at doors and windows.

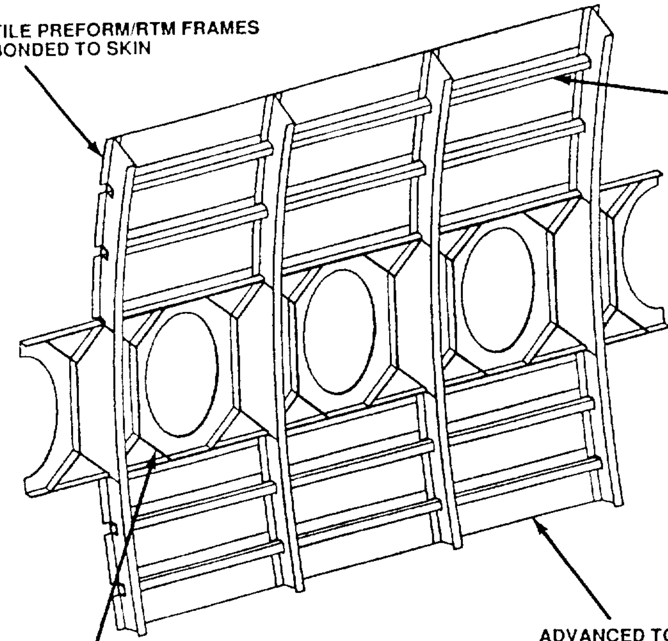

Figure 9: Side Baseline Design Concept and Fabrication Processes Near the Window Belt.

Skins for both side quadrants will also be produced in a batch tow placement. The skin thickness of side quadrants is close to minimum gage approaching the crown and relatively thick near the keel. Increased skin gages also occur locally near doors and windows. Automated batch processing and significant amounts of ply tailoring possible with the advanced tow placement method led to its selection for the side quadrant.

The same baseline processes and material forms were chosen for side panel stiffener and frame elements as were selected for the crown. The window and door frame design details were chosen to be textile preforms fabricated in an RTM process. Autoclave fabrication of full side quadrant segments (each side ≈ 251 in. by 374 in.) was planned to include wet skin and stiffeners, cobonded with frames (circumferential and window belt).

Keel: A variation of design concepts from Family D (sandwich) was chosen as the keel baseline. The variation includes a thick laminated plate to panelize the keel beam chords. The thick plate gradually transitions into a sandwich panel as axial compression loads decrease away from the section splice. The sandwich facesheets have tapered thickness in the transition zone. Figure 10 shows the heavily loaded end of the keel panel baseline near the section splice.

This innovative panelized concept was chosen for the keel quadrant baseline for several reasons. First, it avoids problems in fabricating and splicing two large composite keel chord members. Large fastener hole diameters needed to mechanically splice discrete composite chord members would cause a significant knockdown on the allowable strength. The panelized concept alleviates this problem to some extent. The blended thick laminate/sandwich construction also yields a constant gage panel that avoids problems in attaching frames and other elements to a skin/stringer design having skins with considerable thickness taper.

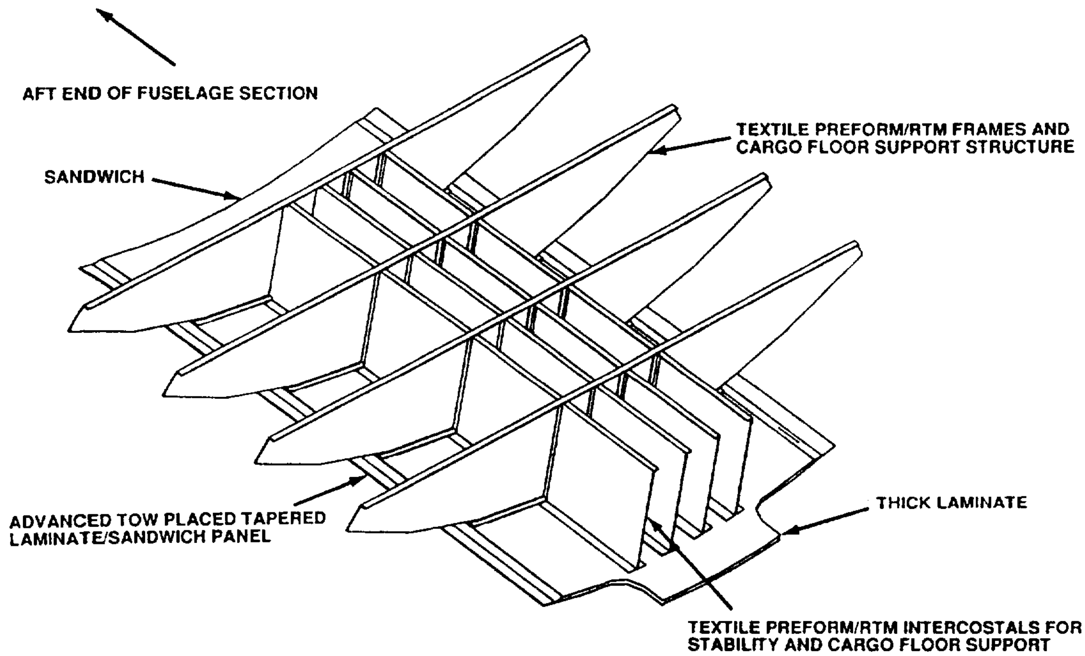

Figure 10: Keel Baseline Design Concept and Fabrication Processes.

Face skins for the keel panel will also be produced in a batch tow placement process. Again, automated batch processing and significant amounts of ply tailoring possible with the advanced tow placement method led to its selection for the keel quadrant. The sandwich core will be machined with a constant taper to keep the keel panel at a constant gage as laminate plies are dropped.

Keel baseline elements include intercostals and full-depth frames, both of which will be stiffened. These elements serve dual roles in overall panel stability and cargo floor support. Note that intercostals are discontinuous at the frames. Baseline material forms and processes for both these elements are textile preforms and RTM, respectively. Frames and intercostals will be mechanically attached to shear tied blade elements on the fully cured keel panel. These blade elements will be co-bonded to the keel panel at cure. Keel quadrant segments (≈ 72 in. by 374 in.) will each be small in comparison to side and crown panels; however, the weight per unit area will be relatively high.

Technical Issues

The most critical manufacturing issues associated with baseline concepts selected for ATCAS relates to final assembly. Crown and side panels have bonded stringers and frames, while the keel panel is sandwich with bonded frames. This eliminates element assembly steps and part count, but high bending stiffness of the baseline panels will limit attempts to deform them into shape prior to splicing. Figure 11 illustrates some of the problems on a diagram of the full baseline crown panel. Variations in locational tolerances of stringers and frames is critical to their alignment at circumferential and longitudinal splices, respectively. Overall panel warpage may also be an issue due to the local unsymmetric layups at bonded elements.

Another critical manufacturing issue is the quality control of quadrant panel fabrication processes. Quadrant panel cost benefits assume that large panels will not be rejected due to manufacturing defects. In order to avoid adding unnecessary costs to the manufacturing process, the panel fabrication quality required for acceptable performance must be understood.

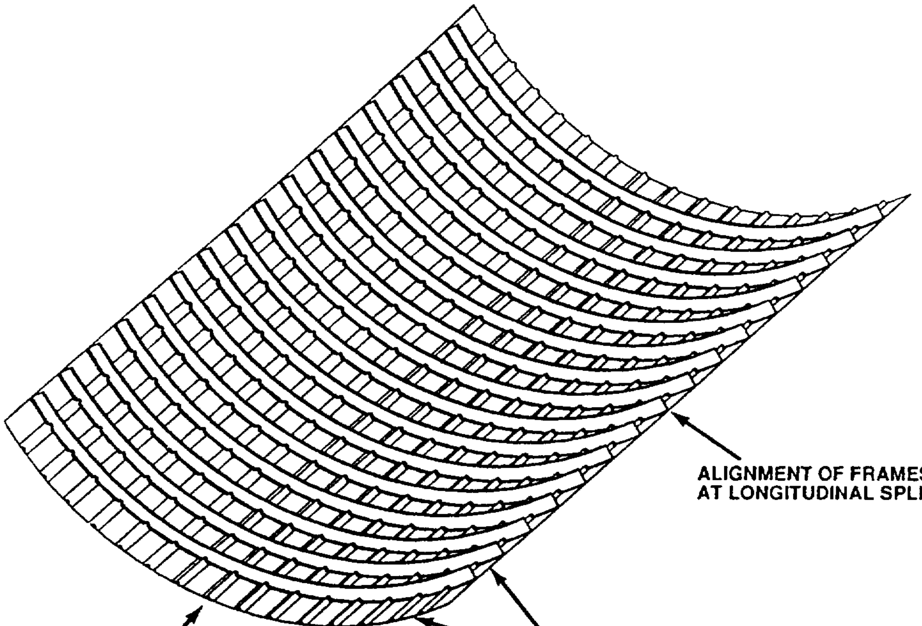

Figure 11: Assembly issues for the crown quadrant panel.

Crown: The fuselage crown area is the simplest quadrant in terms of design detail and manufacturing complexity. A smaller number of technical issues are also associated with the crown. Two critical manufacturing issues were discussed at the start of this subsection. Tension damage tolerance is the most critical structural issue for crown panels. Analysis and tests are needed to evaluate the effects of dynamic pressure release on tensile residual strengths following a through-penetration impact event (e.g., engine blade penetration). Other major issues for the crown baseline which will be addressed in ATCAS are listed in Reference 1.

Window Belt (Side): The fuselage side quadrants have considerably more design detail and manufacturing complexity than the crown. Many of the crown technical issues are also critical to side panel locations above the window belt. The two critical manufacturing issues that were discussed at the start of this subsection are of greatest concern for the side quadrants due to their size. The lower portion of side quadrants (i.e., approaching the keel) have considerable combined load interactions. The combined effects of axial compression, inplane shear, and hoop tension on damage tolerance need to be understood. Other major issues for the side baseline concepts which will be addressed in ATCAS are described in Table 1.

Keel: The aft fuselage keel quadrant poses one of the most difficult design challenges for applications of composites to transport fuselage (i.e., load redistribution of very high compression loads entering the fuselage shell at the keel beam attachment). It also has considerable design detail and manufacturing complexity related to the cargo bay floor. The critical manufacturing issues that were discussed at the start of this subsection are of particular concern for the baseline keel quadrant due to its high stiffness. Other technical issues listed for the crown and side quadrants are also critical to the keel. These include side issues number 5, 6, and 9 from Table 1 for circumferential frames. Note that loads affecting durability of keel frame to panel adhesive bonds differ from those in the crown. The 2 ft. deep baseline keel frames and intercostals also add manufacturing complexity to the textile preform and RTM fabrication processes. Other technical issues for the keel are given in Table 2.

Issue	Description
1.) Damage Tolerance of Pressure Loaded Panels With Large Penetrations	This issue involves failsafe load and damage conditions. The most critical damage geometries are expected to be slender notches oriented along the longitudinal axis (e.g., Reference 3). The effectivity of bonded frames as "tear straps" needs to be determined. The scenario of a penetration that severs a frame and skin must also be studied.
2.) Impact Damage Resistance and Tolerance of Stiffened Panels Near the Keel	Numerous in-service impact scenarios are possible in the lower portion of the side quadrant. These include stones, runway debris and ground handling equipment. Studies are needed to insure that the structure is resistant to damage occuring for the full range of impact events and to characterize damage for residual strength predictions. The effects of combined compression and shear loads representative of the lower side quadrant must be considered. An understanding of material, structural, and laminate variables affecting impact damage resistance and tolerance is needed to promote low-cost, robust designs.
3.) Shear Stability and Damage Tolerance Near Panel Cutouts Such as Windows and Doors	Window & door elements such as frames, door stops, and intercostals insure adequate strength and dimensional stability in areas of shear and pressure load redistribution. Design and fabrication of these elements must consider damage scenarios which complicate load paths. Current plans project window frame modules cobonded to the skin; however, potential debonding problems may require through-thickness reinforcement such as composite rivets for adequate performance.
4.) Efficient Laminate Thickness Tailoring at Door & Window Cutouts	An increase in laminate thickness near large cutouts such as windows and doors is required for stiffness, stability and strength. Since material tends to be a major cost center, it is desirable to understand the manufacturing options and mechanics issues that will enable thickness tailoring to save cost and weight.
5.) Fiber/Resin Distribution of Frames, Window and Door Design Details After RTM Processing	Performance, warpage, and additive dimensional tolerance control of complex geometries such as curved frames relates to fiber/resin distribution. These factors must be considered in seeking an answer to the scale-up issue of the element sizes feasible for RTM processes. Assuming a suitable cure cycle and tooling approach, the fiber/resin distribution of traditional tape and tow materials is most strongly dependent on the prepreg operation. Receiving inspection tests add costs to these materials to insure prepreg of acceptable quality. Both resin infusion and part cure occur during RTM processing. Cost efficient methods of controlling the fiber/resin distribution and, hence, quality of RTM parts must be established.
6.) Handling and Storage of Cobonded Design Details Before & After RTMing	Methods of handling dry preforms must avoid distorting the textile weave pattern (e.g., fiber orientation) prior to cure. This includes the operation used to drape preforms into tools for RTM processing. After RTMed parts are cured, they must be stored to avoid surface contamination prior to cobonding with side quadrant panels.
7.) Nondestructive Inspection of Complex Window and Door Frame Detail Geometries	Methods for evaluating the quality of complicated part geometries (e.g., corner radii in window frame modules) need to be developed and demonstrated. Collaborative efforts with structural analysts is also required to determine the effects of defects and hence, support development of robust designs and quality control specifications. The approach established should ask the question of "what manufacturing quality is needed to insure performance standards ?". This would avoid specifications that eliminate benign defects and add unnecessary costs to the fabrication process.
8.) Performance of the Frame Mousehole Design Detail	This design detail simplifies the skin/frame co-bonding operation but adds stress concentrations in frame and adjacent skin material that needs to be analyzed and tested. Higher stresses near the mousehole may lead to a need for additional frame material. Sufficient damage tolerance for skin penetrations located near the frame mousehole must also be established. Cost trades between reduced bonding labor and increased material needs to be understood to minimize total costs.
9.) Durability at Load Transfer Details (Bonded Elements and Mechanically Fastened Splices)	Durability of composite fuselage design details needs to be studied. Cyclic pressure load conditions are expected to drive the design of frame/skin adhesive joints. This pressure pillowing problem needs to address creep/fatigue interactions using analysis and tests. Combined cyclic load conditions also pose a significant problem for longitudinal and circumferential mechanically fastented joints. The combined loads include pressure and reversed inplane shear. The effects of environment and real time on damage accumulating in material surrounding the bolt hole will need to be considered.
10.) Skin Gage to Satisfy Hail Impact Criteria	Structural tailoring of the top of side panels is limited by the miminum skin thickness required to suppress visible hail damage. This avoids high repair costs for multiple-site impact damage caused by severe hail storms.

Table 1. Technical Issues for the Side Quadrants.

Issue	Description
1.) Impact Damage Resistance and Tolerance of Various Keel Panel Locations	The thick laminate/sandwich construction for baseline keel panels yield unique characteristics to consider in impact damage resistance and tolerance problems. Added laminate thickness has been shown to yield higher residual strengths for a given impact energy (Reference 4). However, the relatively small shell diameter to thickness ratio of a panelized keel and interlaminar stress redistribution due to many ply dropoffs may complicate the problem. The effects of combined compression/shear/pressure load conditions on post-impact residual strength need to be studied.
2.) Through Penetration Damage Tolerance of Various Keel Panel Locations	Failsafe constraints such as through-penetration damage may drive the design of various locations along the keel panel length. For example, added impact damage resistance at the thick laminate end of the panel may be such that ultimate load/barely-visible-damage criteria cause little strength reduction (note: this can occur when using a maximum impact energy as a threshold). Through-penetration damage tolerance will also have to consider the effects of combined compression/shear/pressure load conditions and ply drop-offs.
3.) Panel Stability With Major Compression Load Redistribution	There is likely coupling between residual strength, stiffness, and stability for a heavily loaded panel such as the baseline keel concept. Analysis and tests are needed to ascertain key variables affecting stability of the innovative keel design. Local eccentricities of a sandwich panel with internal ply drops and wedged core could be amplified by the presence of damage. The retention of frame-to-panel bond strength is crucial to stability along the panel length. Stability of the thick laminate at the forward end is also dependent on the effectiveness of intercostals for providing a side boundary condition.
4.) Process Cure Cycle for a Panel That is Thick Laminate On One End and Sandwich On the Other	A suitable cure cycle needs to be developed and demonstrated for the baseline keel concept. Traditional low density composite honeycombs are unable to withstand the high pressures needed to cure some toughened matrix materials. One solution to this problem is to precure laminate portions of the panel prior to adhesive bonding with the honeycomb core. This may prove costly and lead to adhesive bond problems if the precured thick laminate section is warped. Another solution is the use of foam core materials that are able to withstand pressures needed for cocuring with the laminate.
5.) Efficient Laminate Thickness Tailoring for Load Redistribution	Interlaminar stresses must be considered in selecting ply drop-off sequences as compression loads decrease from the forward to aft ends of the keel quadrant. Efficient processes such as automated tow placement that can drop plies with minimum material waste are sought. Analysis and test are needed to select materials best suited for the load conditions.
6.) Laminate Material Forms for the Baseline Keel	Strong trade-offs between performance and cost are anticipated by the DBT when attempting to select the optimum keel material. Crucial material characteristics include interlaminar shear load transfer, impact damage resistance, and through penetration residual strength. High interlaminar shear stresses near numerous ply drop-offs in the keel panel suggests a possible need for additional resin to enhance load transfer. This may be achieved by increasing overall towpreg resin content or locally adding adhesive at ply drops. A compliant, toughened adhesive is expected to work best for increasing both the interlaminar shear load transfer and impact damage resistance. The through-penetration damage tolerance also needs to be studied because it could conceivably drive the design of toughened materials.
7.) Core Material Form for the Baseline Keel	An impact damage resistant sandwich concept is needed for the keel baseline. Past work (e.g., References 3 and 5) have indicated an inherent weakness in traditional composite honeycomb and polymeric foam materials whereby impact causes significant damage that leads to the loss of facesheet stability and decreased compressive residual strength. Examples of improvements in impact damage resistance include higher density core materials and a foam with re-entrant cell structure (Reference 6). Other factors such as curvature and core/facesheet interactions also need to be studied.
8.) Thick Laminate Keel Panel Splice Heavily Loaded in Compression	Several technical issues need to be considered for heavily loaded mechanical joint attachments between thick laminates. Small fastener diameter-to-thickness ratios affect laminate bearing capability, and, due to typically low interlaminar shear moduli, will also increase fastener flexure. Large holes required to mechanically attach thick laminates directly affect bypass-dominated failures and are expected to change the bearing-bypass interaction.
9.) Repair of Thick Laminate/Sandwich Panels With Bonded Design Details	Repair is an issue at both ends of the baseline keel panel. Mechanical attachment of repair plates will be difficult for sandwich panel construction. Major repairs involving the base panel and portions of the full depth frames will also be laborious. Bonded repair methods for surface damage will need to consider difficulties in curing portions of thick laminates and sandwich panels in the field. New repair methods that can be performed more simply and with minimum cost are needed for thick laminate and sandwich panels.

Table 2. Technical Issues for the Keel Quadrant.

ATCAS SIX YEAR PLAN & PROGRESS TO DATE

Crown, keel, and side areas of the aft fuselage section will be studied in Phases A and B of the ATCAS program. These two phases span a five year time period ending in 1994. An optional addition to Phase B for fabricating a large pressurized panel test fixture and performing combined load tests is scheduled to occur from 1993 to 1995.

Figure 12 shows a timeline of the six main areas of development and verification tasks within the ATCAS program. Comprehensive schedules were created in each of these areas to integrate design, manufacturing, structures, materials, and test tasks. Crown, keel, and window belt areas will initially be studied separately because each has unique manufacturing and structural issues to be resolved. Efforts are spread such that the most difficult problems receive greater attention. For example, Figure 12 shows that 2.5 years are dedicated to crown panels, while keel studies will last a full 5 years.

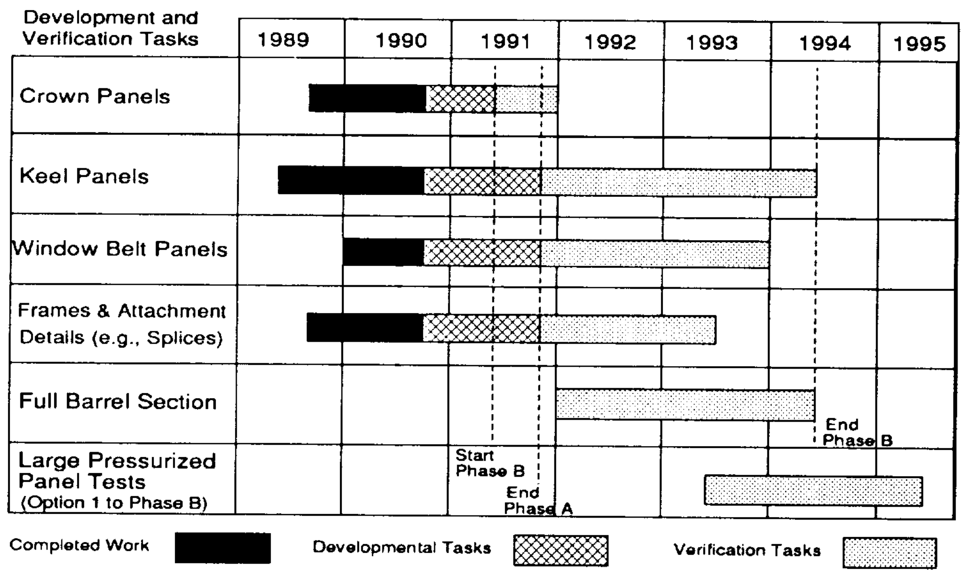

Figure 12. Development & Verification Timeline for ATCAS

Development and verification tasks for frames and attachment details support each quadrant. The final design optimization efforts with these elements and splices are left until the "Full Barrel Section" effort at the end of Phase B. This will promote assembly cost savings by striving for part commonality throughout all regions of the study section.

The three step DBT approach described earlier for achieving ATCAS cost and weight saving goals will be applied to each quadrant. Note that design activities for side quadrants are associated with the window belt timeline. The first step, baseline concept selection, has been completed for each quadrant. Global evaluation has been accomplished for crown panels and is currently underway for the keel quadrant. This second design step is scheduled to be completed for all quadrants by the end of Phase A, substantiating concepts chosen for verification tests with detailed cost and weight saving estimates. Local optimization (Step #3) has just begun for the crown and will be completed by early 1991. The time needed for local optimization varies for each quadrant depending on the engineering efforts required to overcome the associated technology barriers. For example, local optimization for the keel lasts more than 2.5 years.

There is considerable overlap in technology issues that need to be addressed for each quadrant. Fabrication, analysis, and testing efforts were scheduled to group common tasks. Figure 13, which is a modification of the ATCAS quadrant diagram (i.e., Figure 5), shows that many of the side quadrant technical issues will be addressed by crown and keel work tasks. The side panel manufacturing and test efforts will include windows, but not doors. Keel panel manufacturing and test studies will include compressive load redistribution approaching the forward end of the section but not the actual keel beam splice. Although doors and the keel beam splice are not included in ATCAS test and manufacturing hardware, both are considered in the design cost and weight estimates.

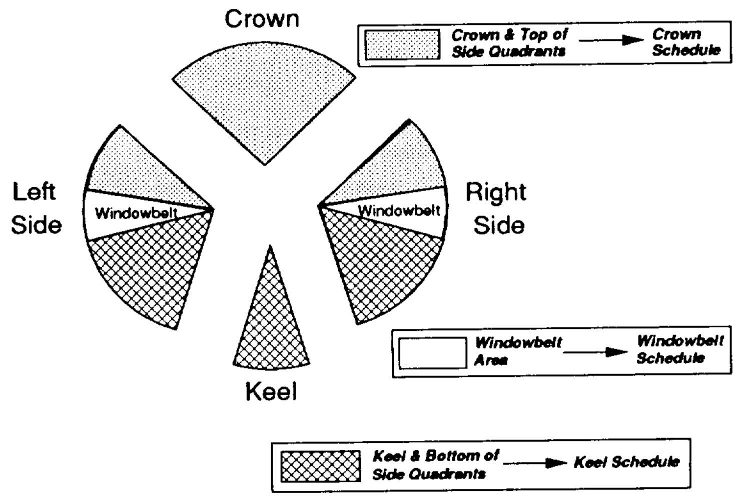

Figure 13. Schedules for Tracking Fabrication, Analysis, and Test Tasks

Industrial subcontractors and other Boeing groups play important roles in ATCAS. Early experiences suggest that the integration of diverse expertise from groups outside the immediate ATCAS team (Boeing Commercial Airplanes) is crucial to the development and verification of advanced technologies. Figure 14 shows groups that have supported ATCAS to date.

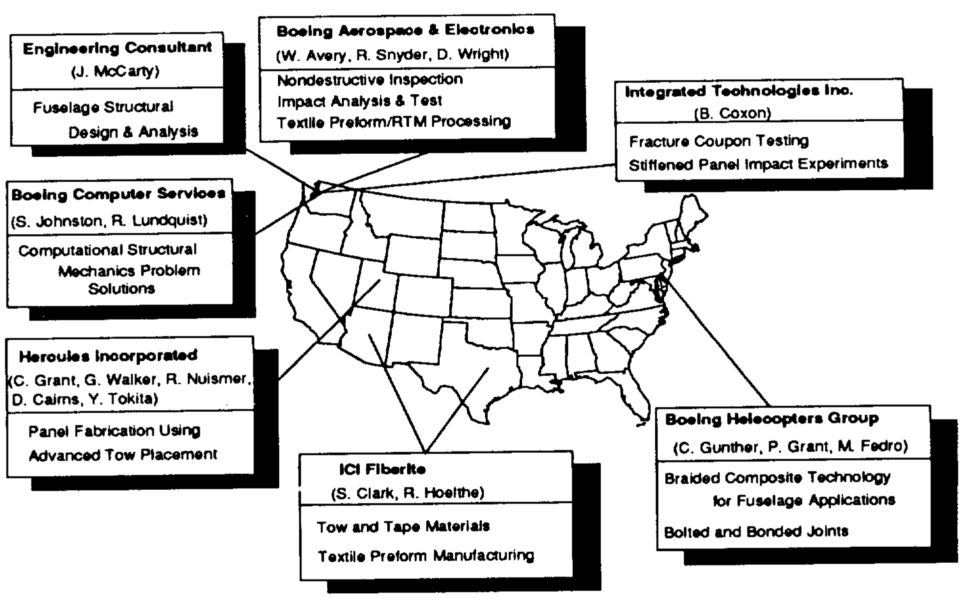

Figure 14. Other Boeing and Industrial Groups Supporting ATCAS

As shown in Figure 15, several university subcontracts have also been issued to support ATCAS. The approach taken to infuse universities in ATCAS has been beneficial to both parties. The Boeing/NASA ATCAS goal of advanced technology development complements the universities' engineering goal for improved education. Each university subcontract was defined to start with fundamental research and end with applications directly supporting work on a technical issue in ATCAS. The engineering tools developed at universities include analysis methods, test techniques, material characterization, and manufacturing developments. In return, the students education is supplemented with an understanding of fuselage technical issues and the opportunity to apply their research to a "real world" engineering problem. Secondary benefits from university infusion have included a cost-effective use of ATCAS funds, and budget for graduate student programs.

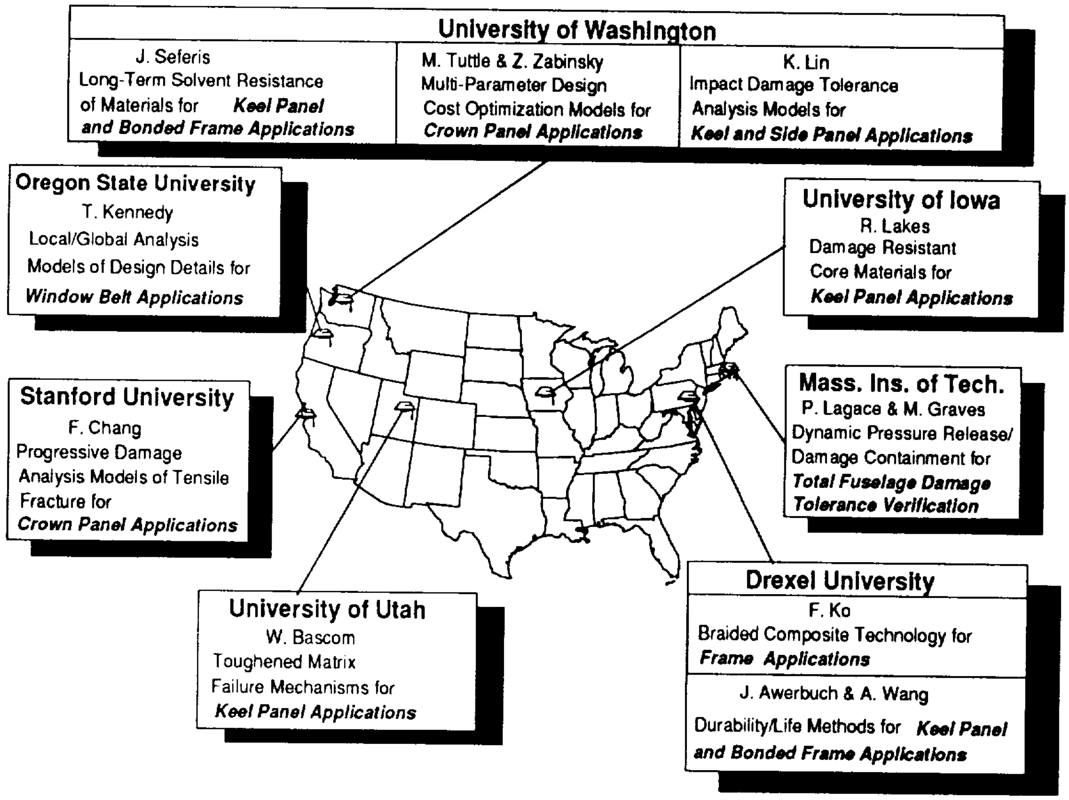

Figure 15. Integration of University Subcontracts in ATCAS

Crown Panels

Global Optimization: Crown panel efforts started in the fall of 1989. Most of the work performed to date supported the global evaluation of design and manufacturing concepts. Two designs from each of three families were developed for global optimization of the crown quadrant. Each design was sized considering multiple load cases, damage tolerance, and assembly design details. The three families were B, C , and D (see Figure 3 for family definitions). A detailed fabrication and assembly plan was developed for each design. These were used to estimate weight, material costs, and labor rates. Both recurring and nonrecurring (minus capital equipment) costs were estimated assuming specified groundrules (e.g., 300 shipsets at a rate of 5 per month). A synopsis of the results from global crown studies appears on the following paragraphs. A more complete account of this effort appears in Reference 1.

The two designs and manufacturing plans for each family varied material types, manufacturing processes, and structural details. This helped to establish a range of cost and weight variation for each family. Design trades within a family also yielded data on cost centers and variable interactions crucial to local optimization studies.

The majority of weight for all designs was in the skin where tension damage tolerance was found to drive skin thickness and layup of most of the crown panel area. Hail impact requirements also controlled the skin gage for the aft end of some panels. Stringer thicknesses were driven by reversed load stability requirements. Both skin and stringer gages near panel edges were controlled by joint bearing requirements.

Figure 16 shows the final results from global optimization. All composite crown designs studied were found to be cost and weight competitive relative to the metallic benchmark. Relative weights for composite designs ranged from 49% to 80% of the metal. The estimated relative manufacturing costs for composite concepts ranged from 99% to 139% of the metal. When considering an economically acceptable cost increase per unit weight savings (i.e., concepts to the left of the slanted solid line in Figure 16), all composite designs showed an advantage over the metal benchmark.

Aluminum costs were dominated by labor, while material and labor costs for composite designs were close to equal. Composite designs were competitive with the metal benchmark primarily because reduced assembly labor offset lower aluminum material costs. For example, a composite crown panel had 10,000 less fasteners than the metal counterpart. This relates to large composite quadrant panels with bonded elements for Family C.

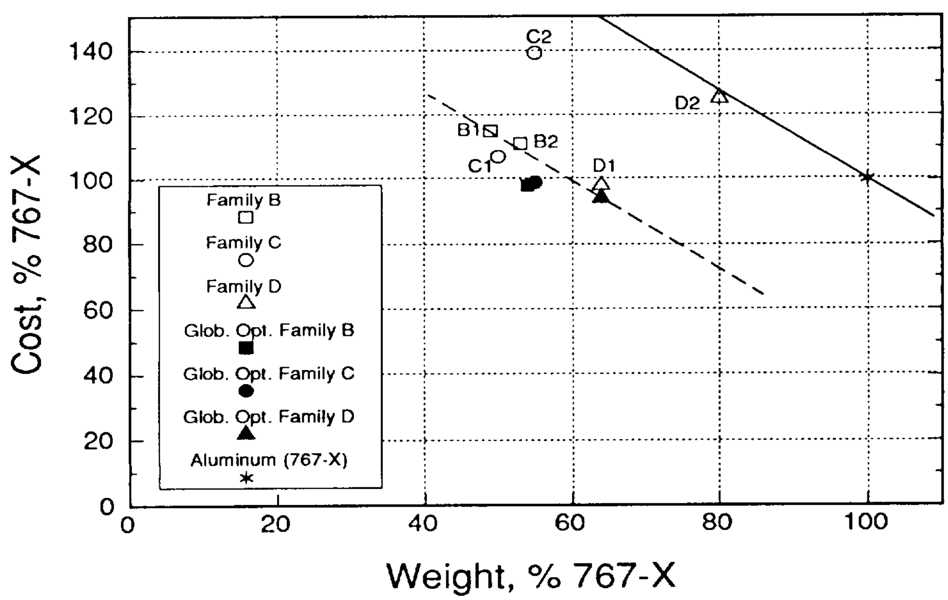

Figure 16. A Comparison of Results from Global Optimization Studies and the Metallic Benchmark.

Figure 16 also shows globally optimized family designs derived by mixing and matching the best features of concepts studied (e.g., cost-efficient materials and processes). The most promising family was selected based on results from this exercise and an evaluation of the potential for further cost and weight optimization. Globally optimized Families B and C were both found to be nearly equivalent in cost and weight. Family D yielded a lower cost with some weight penalty (i.e., 94% the cost and 64% the weight of metal). The weight increase for Family D was not found to justify the cost savings. This is shown in Figure 16 where concepts to the left of the dashed line represent an acceptable cost increase per unit weight savings. Family C was chosen over Family B, despite greater manufacturing risk, due to good local optimization potential and bonded frames which may help damage containment.

Local Optimization: Local optimization of crown panels is currently underway. This task will further refine the design by attacking cost centers identified in global optimization. The most significant cost centers for crown panels were found to be skin, stringer, and frame fabrication; panel bonding (i.e., element subassembly, bagging and cure); and fasteners required for quadrant assembly and body join. The relative percentage of material and labor components of cost varied for individual fabrication and assembly steps. A rough estimate of the local optimization potential for composite crown panels indicated cost savings up to 25% (relative to the metallic benchmark) within the range of acceptable weight penalties.

The use of a high performance fiber to reduce skin weight was not found to be cost effective in global optimization of crown panels. This relates to the trade between a higher material purchase price and the costs saved from added performance capability. Attempts to reduce the composite material cost center for crown panels will include studies with graphite/fiberglass hybrids. The high tensile strength and low cost of fiberglass makes it a candidate for crown applications. The economically acceptable increase in weight per unit cost savings will be considered in this evaluation.

The relatively low aluminum material costs generally allow an effective trade of added weight for reduced labor. High composite material costs are expected to lead to relationships between cost and weight that differ from those of metals. A software design tool that includes cost and mechanics constraints is being developed by the University of Washington to support the optimization of crown panels (see Reference 7). Figure 17 shows this optimization tool schematically. Critical design variables are expected to include material type, stringer geometry, and laminate thickness.

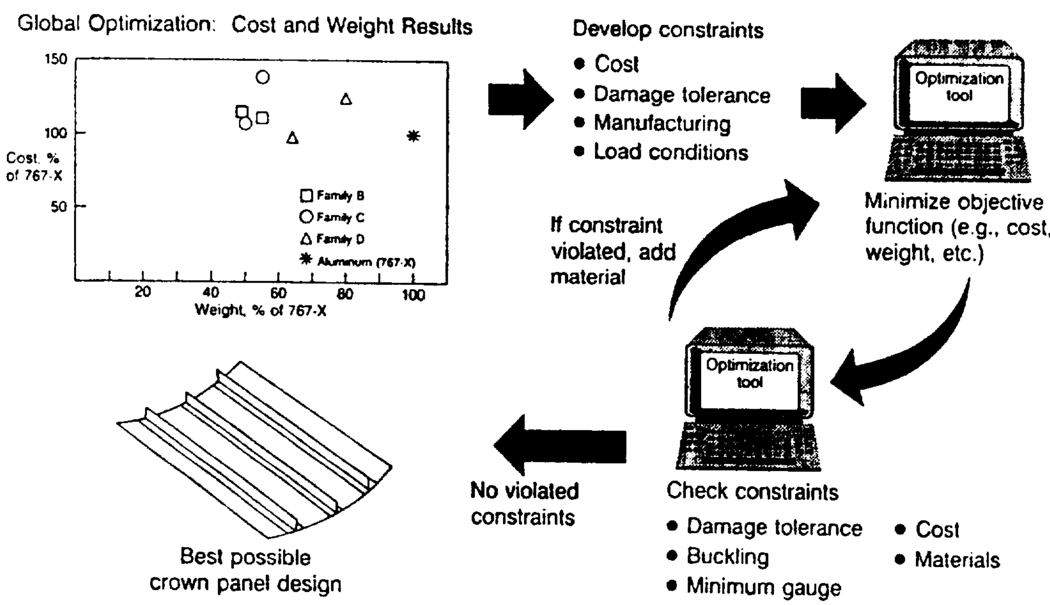

Figure 17. Local Crown Panel Optimization Tool

Several other factors will be considered to reduce cost in local crown optimization. These include the manufacturing approach to panel subassembly and the use of low-cost composite fasteners. Efficient processes for stringer and frame fabrication are also sought. Considerable costs were saved during global studies by envisioning batch processes for these elements; however, their costs were still high relative to the metallic counterparts. One potential cost savings may be in the use of tow placement rather than CTLM to layup stringer charges. This relates to projections that the future costs of prepreg tow will be less than that of tape. A continuous RTM process involving textile preforms may also be suitable for low-cost stiffening elements.

Analysis, Fabrication, and Test: Tension damage tolerance is the most critical performance issue for crown panels. Several damage tolerance analysis methods have been developed and implemented as mechanics constraints in the local optimization software shown schematically in Figure 17. These procedures, which utilize a characteristic dimension failure criteria, include the effects of pressure, panel curvature, bonded stiffening elements, and material anisotropy. Figure 18 plots typical results from residual strength analysis showing an interaction between pressure, panel curvature, and local bending stiffness. Pressure is shown to decrease residual strength due to local bending at the notch tip that increases the stress concentration. A sandwich panel construction alleviates some of the effects of pressure by increasing local bending stiffness. For this reason, a sandwich panel design was selected as a backup to the crown baseline.

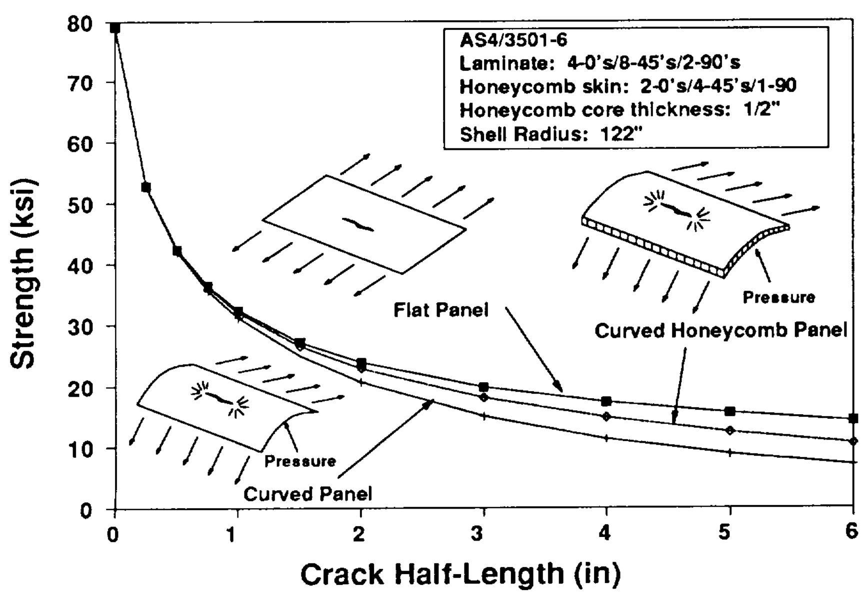

Figure 18. Predicted Tensile Strengths of Damaged Panels Subjected to Inplane and Pressure Loads

In addition to the simplified analysis described above for predicting tensile residual strength, a more complete progressive damage model is being developed at Stanford University. The Stanford models will be used during final test verification to evaluate the growth and accumulation of local damage that occurs prior to catastrophic failure. To date, progressive damage models have been developed to account for fiber breaks, matrix cracking, nonlinear shear behavior, and fiber/matrix splitting. Future enhancements will incorporate the effects of nonlinear longitudinal moduli, delamination, variable notch geometry, combined load conditions, and panel element geometries.

Advanced tow placement and the batch quadrant processing concept were shown to be efficient in detailed cost studies for crown skins. Tow placement layup costs were found to be on the order of 20% of the skin material costs. Since skin constituted the largest portion of panel weight, an efficient layup process helped to lower total composite crown costs. Advanced tow placement is ideally suited for the graphite/fiberglass hybrid concept being considered for reducing crown material costs. Tow-placed intraply hybrid panels can be fabricated without affecting process efficiency. Figure 19 shows one of the four graphite/fiberglass hybrid panels fabricated in ATCAS to date. Additional discussion of advanced tow placement manufacturing trials completed in ATCAS appear in the next section on keel panels.

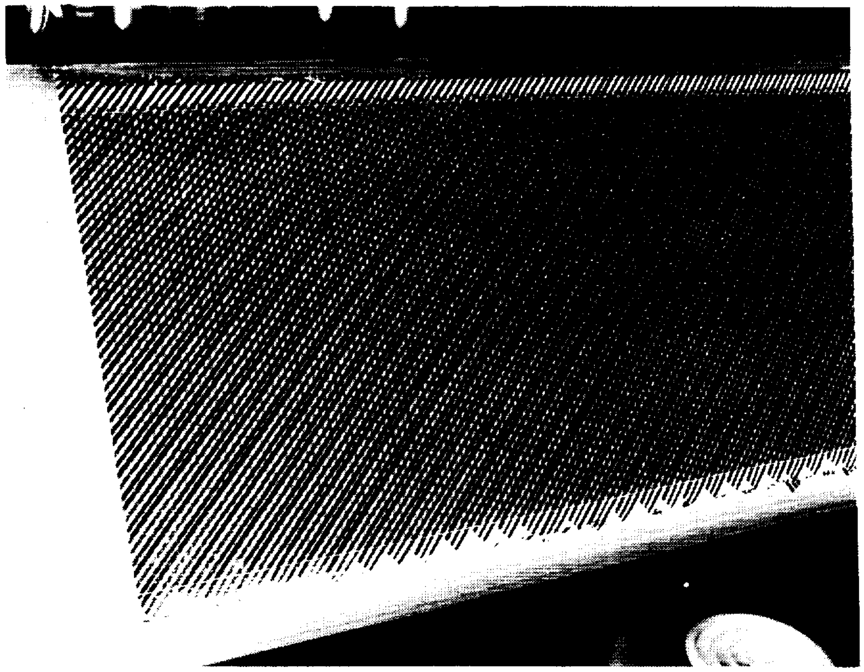

Figure 19. Tow Placed AS4/S-Glass Hybrid

Specimens cut from the hybrid panels will be used to evaluate notched tensile residual strength. The base material type in these studies is AS4/3501-6. Hybrid material and process variables under consideration include hybridizing fiber type (S-glass and T1000), percent hybridization (25% and 50%), and repeating unit tow width (0.35 and 1.1 in.). The screening test variables include notch type (hole, slit, and impact induced through-penetration) and notch size (0.25, 0.875, and 2.5 in.).

Plans and schedules in ATCAS are coordinated to yield test panels from process verification studies. Fabrication of crown panel demonstration hardware is scheduled for the first half of 1991. This effort will start with some tooling trials and end with the fabrication of several panels, the largest of which is 8 ft by 10 ft. Current plans will emphasize the baseline design (Family C, with bonded stringers and frames). If problems occur due to the complex bonding operation or insufficient tensile damage tolerance an alternate plan, involving sandwich panels with bonded frames, will be implemented.

Verification tests using stiffened panels (three to five stringer) that represent portions of the optimized crown design will occur during 1991. These will include (1) uniaxial panel stability tests for reversed load conditions (with and without critical impact damage), (2) impact trials to validate that minimum gage/hail requirements are satisfied, and (3) tensile damage tolerance tests (pressure, uniaxial, and biaxial) for various through-penetration damage scenarios.

Keel Panels

Aside from baseline concept selection, little keel design work has been completed to date. Initial keel work tasks have included analysis, fabrication, and tests to address some of the critical issues listed earlier. Specifically, issues number 1, 6, and 7 from Table 2 have been studied during the first 16 months of ATCAS. Results from these studies will support final material selection and detailed design. This subsection will summarize work on each of the three issues, followed by a description of the large keel hardware tests planned towards the end of ATCAS.

Designed Experiment for Fuselage Panel Impact Resistance: All quadrants of the fuselage have technical issues related to impact damage resistance. A test program was defined early in ATCAS to evaluate the effects of thirty two combinations of material, laminate, structural, and extrinsic variables on impact damage resistance. The experiment was designed to ascertain main effects with a minimum number of tests. Some of the details of this experimental design are described in Reference 8. The desire to integrate ATCAS tasks (e.g., manufacturing trials and test hardware) led to a more general plan for panel fabrication and usage than would have been required for impact screening alone. Figure 20 shows some of the manufacturing and performance issues addressed by this initial fuselage panel fabrication effort. Large panels were fabricated to study manufacturing scaleup issues such as low-cost tooling concepts in the presence of ply dropoffs.

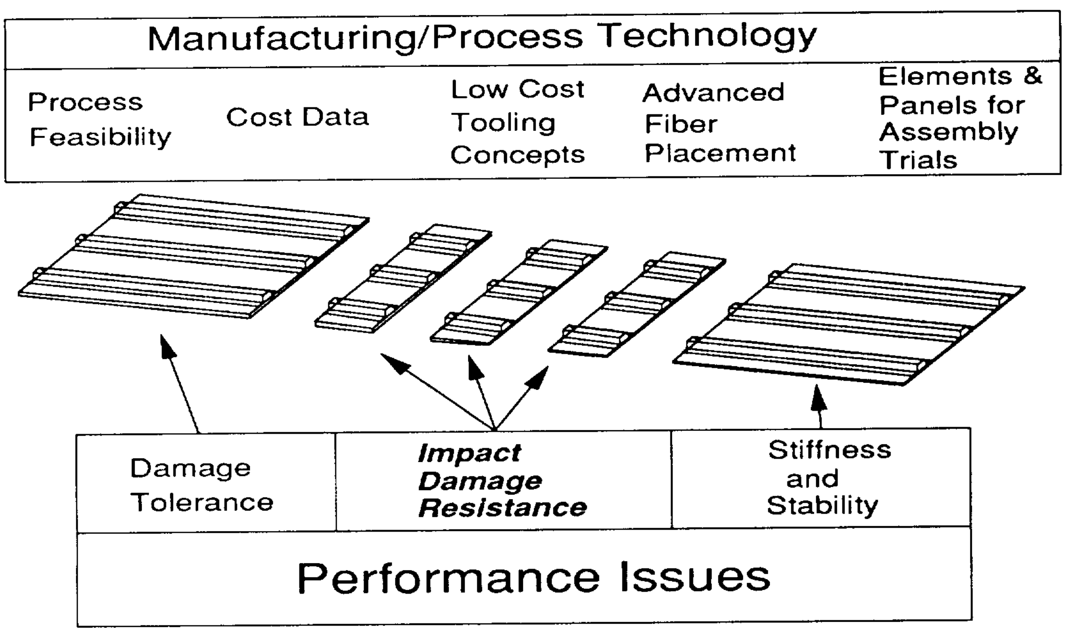

Figure 20. Multifunctionality of the Initial Fuselage Panels Fabricated for ATCAS

Sixteen 110 in long stiffened panels were fabricated to support the tasks shown in Figure 20. Each panel had thick (≈0.18 in.) and thin (≈0.089 in.) ends, with a central transition zone where 12 plies were dropped over a 10 in. length. Note that different portions of these panels were used to study baseline crown, keel, and side quadrant issues. The thick end provided data for the lower portion of side quadrants (i.e., below the windows). The thin end was used for the crown and the upper portion of side quadrants (i.e., above the windows). Finally, laminates in the transition region of the panel were used to fabricate sandwich panels that supported the keel baseline. All activities related to the fabrication of the sixteen stiffened panels were tracked on the keel schedule of ATCAS monthly reports, despite the relationships with other quadrants.

Eight of the sixteen panels were fabricated at Hercules Inc. using advanced tow placement. Figure 21 shows a photograph of one of the tow placed panels. All other panels were processed using tape material forms at the Boeing Company. Drape forming and low-cost rubber tools were used to facilitate fabrication of the hat stiffening element geometry at both companies.

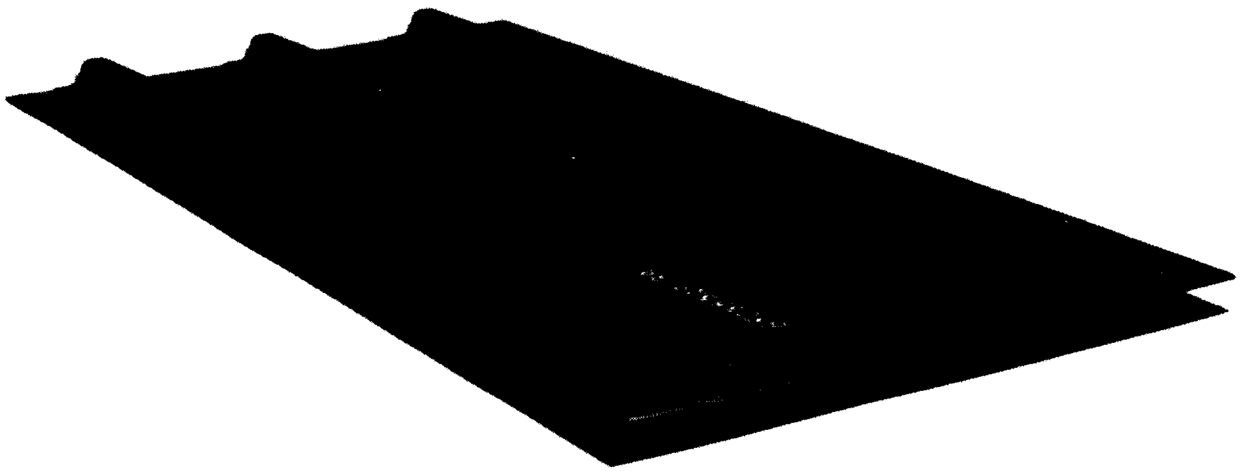

Figure 21. Tow Placed Hat Panel

As discussed earlier, the most critical assembly issue related to cured panel warpage and locational tolerances for bonded elements. The approach used in ATCAS to solve this problem involves three steps. First, manufacturing demonstration hardware will be fabricated with design details. Second, cured panel imperfections will be experimentally measured. Figure 22 shows warpage measurements for one of the hat stiffened fuselage panels. Finally, a suitable analysis method will be developed to predict the warpage and perform sensitivity studies to select design variables that minimize potential assembly problems. Early developments supporting this final step included an ABACUS finite element model that predicted the shape and overall deflection shown in Figure 22 to within 5%.

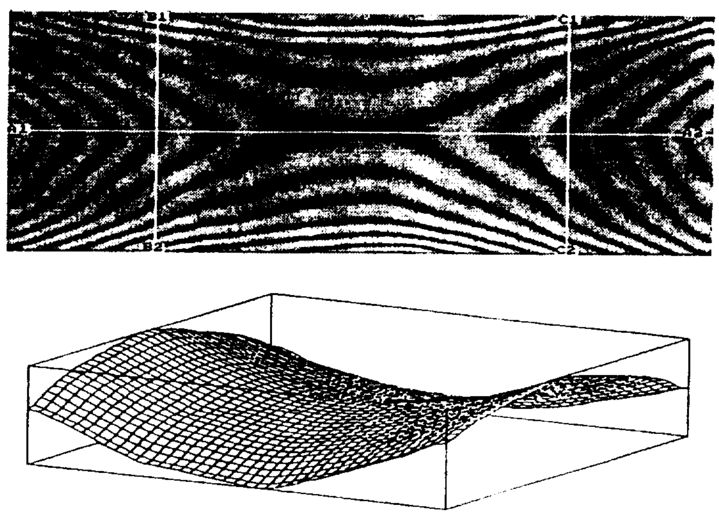

Figure 22. Panel Warpage Measurements Using a Moire' Technique

Toughened Material Models: Composite materials with compliant, resin-rich, interlaminar layers (RIL) tend to have improved interlaminar shear toughness and impact damage resistance. Both appear to be advantages for keel applications. Considerable efforts have been spent in ATCAS to develop analysis tools and generate data bases for toughened materials with RIL (see References 8-12 for more complete documentation).

Toughened materials studies have included (1) material property tests, (2) characterization of failure mechanisms, and (3) analysis method development. Some relationships with the RIL microstructure were found in each area. Mode II delamination toughness was directly related to RIL thickness; however, no such correlation was found to exist for mode I toughness (Ref. 11). The tendency for RIL to suppress delamination during an impact event has been found to lead to fiber failure as an alternate failure mechanism (Refs. 10 and 11). The presence of RIL was found to alter matrix crack resistance, reducing the in situ transverse strengthening effect observed with traditional composite laminates (Ref. 12). Not all analysis methods developed for materials with RIL required an accurate model of the microstructure. It was crucial to simulate the RIL for matrix crack predictions. However, accurate predictions of compressive strength after impact (CAI) were obtained without modeling the RIL.

Impact damage is expected to be a critical issue, particularly in the lower side and keel quadrants. Models have been developed and verified in ATCAS to predict CAI for different composite materials and laminate stacking sequences (Ref. 8-11). Laminate layups and specimen geometries used for material screening received special attention in ATCAS. Models were used to interpret results from experiments. For example, the effects of finite specimen width on CAI were eliminated with the help of analysis. Parametric analysis studies were used to identify key variables affecting CAI, resulting in recommendations for improved material screening procedures (Ref. 9). Figure 23 shows why it is crucial to screen materials over a range of impact energies and correct for specimen width effects.

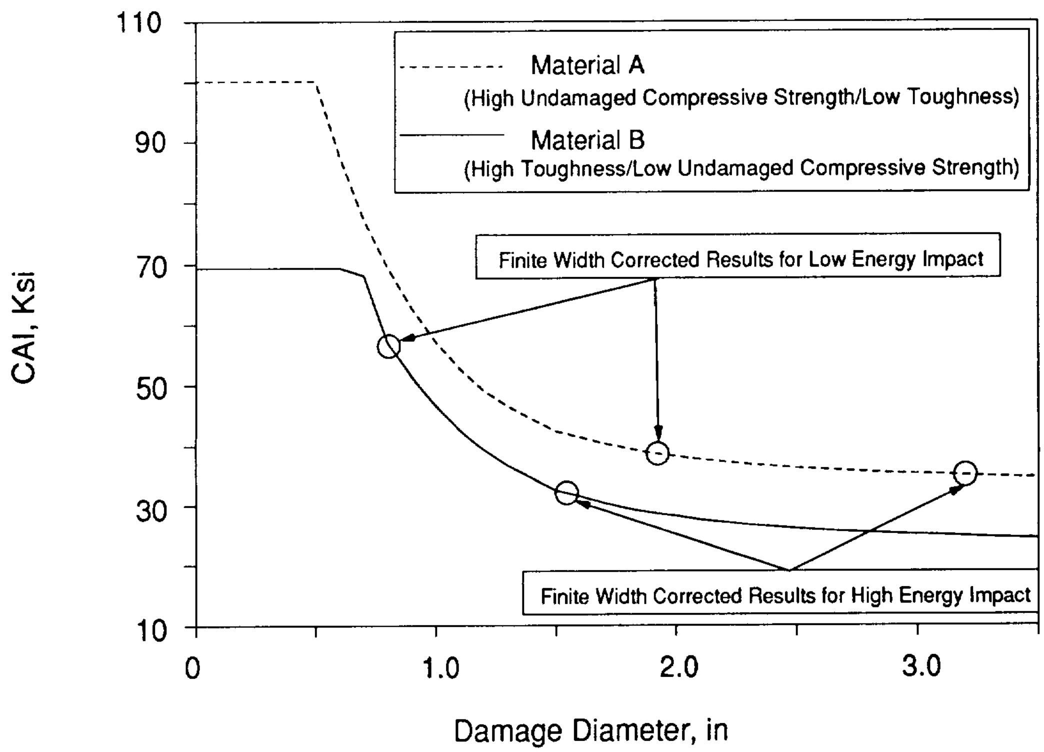

Figure 23. Theoretical Damage Tolerance Curves for Two Materials

Studies are underway in ATCAS to determine optimum fiber/resin combinations and resin contents (both intra and inter-laminar, see Ref. 11) from the standpoint of both cost and performance. Conceivably, lower cost fibers and higher resin contents may acheive the compression performance advantages of a RIL microstructure with reduced costs. The compressive failure strain was found to increase for toughened laminates having higher resin contents (Ref. 11). This attribute may be even greater when considering laminates with significant amount of ply dropoffs, characteristic of the keel baseline. Figure 24 shows that the ATCAS analysis methods developed for toughened materials are general enough to account for variations in resin content.

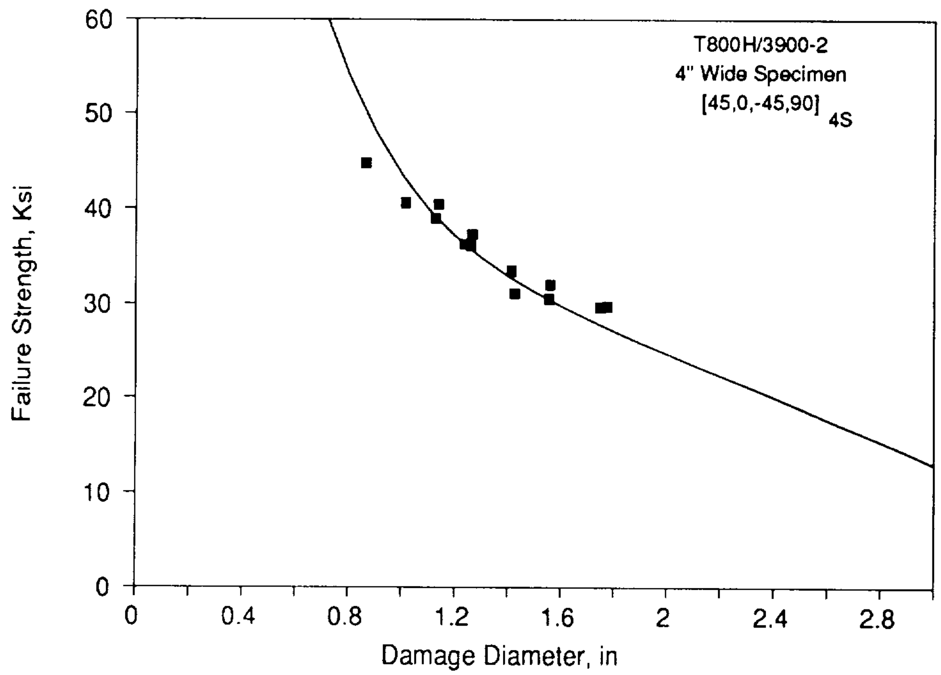

Figure 24. CAI Analysis and Experiments for a Toughened Material With Increased Resin Content (V_f= 0.49)

As shown in Figure 15, the development of toughened material models involves considerable interaction with universities. Two groups at the University of Washington are involved in the separate tasks of developing (1) methods to screen solvent resistance, and (2) general impact damage analysis models. The University of Utah is using microscopy to study relationships between toughened material microstructure and impact damage accumulation. Drexel University is involved with analysis and test characterization of the long-term durability of toughened materials, including environment and real time effects. Results from these studies will be presented in future ATCAS documentation.

Advanced Core Development: As discussed earlier (see issue number 7 in Table 2), damage resistant core materials are needed to facilitate the keel baseline concept. Considerable progress has been achieved in this area with the University of Iowa subcontract. Figure 25 shows a new class of sandwich core concepts which have potential advantages in fuselage applications. Advantages of the re-entrant cell structure which results in a negative Poisson ratio include high fracture toughness and indentation resistance for foam materials. One manufacturing advantage of the negative Poisson ratio is the ability to bend re-entrant foams and honeycombs into cylindrical shapes characteristic of fuselage panels (note that traditional honeycombs tend to deform into a saddle shape under bending loads). Future work with this new material form will include scaleup of a suitable low-cost process; development of ultrasonic inspection procedures; and analysis/test studies on impact damage resistance, environmental sensitivity, and durability.

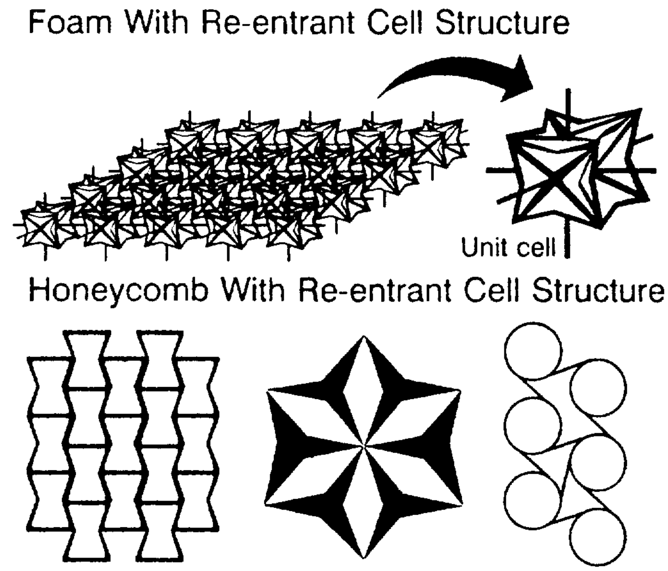

Figure 25. Advanced Sandwich Cores: Foam and Honeycomb

Large Panel Fabrication and Test Plans: A substantial portion of ATCAS funds addresses keel issues with manufacturing demonstration hardware and subcomponent panel tests. Several tests involving small panels (e.g., CAI with three stringer panels) are also planned. As with the crown, process demonstration studies yield panels for large verification tests. Combined compression/shear tests will be performed with curved panels (≈3.5 ft by 5 ft) representative of the lower side quadrant designs. A large curved panel (≈5 ft by 8 ft), representing the aft keel design, will be tested for damage tolerance in different combinations of compression and shear. Repairs will also be performed and verified with this panel. Finally, another large curved panel (≈5 ft by 8.5 ft) will be tested to validate the compressive load redistribution capability of the forward keel design. This panel will also be damaged, tested, repaired, and then tested to failure.

Window Belt Panels

Very little work has been performed in support of the window belt. A baseline concept was selected and the associated technical issues identified. Global optimization of the side quadrants will occur between March and October of 1991. Local optimization of the window belt lasts one year, ending in the fourth quarter of 1992.

As shown in Table 1, several issues (3,4,5,6, and 7) relate to RTM processing of the window frame detail. Manufacturing and supporting technology tasks have been initiated to address these issues. In particular, a request for proposals to fabricate RTM/textile window frame modules were sent to candidate manufacturers. Initial tasks will include coupon tests to determine basic material properties and the effects of defects for the window frame material form. Flat and curved window frame modules will be fabricated in the 1992 to 1993 timeframe to bond to window belt manufacturing hardware and test subcomponents. Analysis methods will be developed in an Oregon State University subcontract to predict the overall performance of window belt panels. The effects of local design details (e.g., frame rib geometry) will be considered in this effort.

Panel and subcomponent tests will be used to verify the window belt design concepts. Included in the larger subcomponents is a curved panel (≈3.5 ft by 3.5 ft) with a central window cutout. This panel will be tested in hoop tension to evaluate the effect of cutout geometry and cutout-doubler configuration. Picture-frame shear tests (≈3.5 ft by 3.5 ft) will be conducted to verify the capability of the most promising window-belt concepts and the accuracy of predictions (load-redistribution and stability). The optimized window-belt configuration, including longitudinal stringers and simulated frames, will be tested under compression/shear loading to provide final verification of the design concept and analytical predictions. This panel (≈5 ft by 8 ft) will also address damage tolerance issues, including impact damage and loss of elements.

Frames and Attachment Details

Design development of frames and splices is integrally linked to other ATCAS efforts. Global optimization of these details will be accomplished with each panel quadrant. Local optimization will be performed in the "Full Barrel Section" effort, near the end of Phase B.

To date, the detail development has focussed on the crown quadrant (Ref. 1). These studies indicated that (1)curved frames have much higher weight-normalized costs than simpler geometries (e.g., skins); (2) braid/RTM processes are the most attractive for frame geometries; (3) recurring fastener costs can be significant, and (4) eccentricities at panel splices are a major fabrication issue. Significant efforts have been accomplished in addressing braided-composites variables and fastener costs.

Plans are in place to address other frame and splice issues. Mechanical joints data will be generated to support the splice design of new material forms selected for use in ATCAS (e.g., graphite/fiberglass hybrids and textile materials). Adhesives suitable for the frame-to-skin bond will also be evaluated. This assessment will include residual strength and durability tests. The latter will include sustained loads characteristic of cabin pressure. Robust splice plates that allow some locational tolerance mismatch between stringers or frames at panel joints will be designed and tested.

Braided Composites: Test plans have been developed to evaluate and compare properties of braided composites formed using two processes: (a) RTMing a thermoset matrix, and (b) consolidation of preforms with commingled graphite fibers and thermoplastic strands. Both two- and three-dimensional braids are being considered in this study. Data will be obtained for unnotched tension; open-hole tension, compression, and inplane shear; CAI; transverse tension and shear; bearing; and crippling. Analysis methods are being developed in parallel, to predict stiffness and strength of braided parts with known fiber architectures. Reference 13 gives additional details on progress to date.

Advanced Fasteners: By working with vendors, major fastener cost centers and potentially low-cost fasteners and/or installation methods have been identified. To date, spin-forming of graphite/thermoplastic rivets appears most attractive. Trial installations of the selected concepts and mechanical tests will be conducted to evaluate cost and strength performance.

Full Barrel Section

The primary objective of work associated with the "Full Barrel Section" timeline shown in Figure 12 is to complete work tasks which provide the degree of technology verification required to commit to development of a full scale barrel section (i.e., a potential Phase C option to ATCAS). The manufacturing steps for each quadrant of the aft fuselage will be optimized to minimize costs of a full barrel section. One of the main design activities will be to evaluate potential cost advantages of a 360°

concept from Design Family H. Local design optimization and verification tests will also be performed with frames, attachment details, and splices in attempts to minimize the number of parts. Any of the long-term research efforts with new material forms will also be completed by the end of ATCAS, allowing them to be included during full barrel design studies.

Large Pressurized Panel Tests

The optional addition to Phase B of ATCAS is scheduled to address dynamic aspects of pressure release following a through-penetration damage event. Additional studies of combined loads characteristic of fuselage bending will be coupled with the pressure release problem. Both analysis and test will be used to obtain solutions to these problems, resulting in additional verification on the damage tolerance of composite fuselage design concepts.

Three main analysis steps appear necessary. The first step involves a fluid flow analysis of pressure released through an opening in a curved panel. The second step is a mechanics problem to determine the stress state acting on the damaged composite structure due to a combination of dynamic pressure release and existing load state. Finally, verified failure criteria need to be developed which account for the combined effect of in-plane and out-of-plane load conditions. Some of the analysis development and coupon test verification for this effort will be performed under university subcontract by the Massachusetts Institute of Technology.

The full scale test fixture, illustrated in Figure 26, will be designed and fabricated to permit testing of large pressurized fuselage panels (≈6.5 ft by 10 ft). Flight conditions will be simulated by attaching a loading frame to a bulkhead. The loads will be reacted through another bulkhead which is attached to a strongback. The interface between the composite test panels and aluminum test hardware will be designed such that panel failure will not damage the test fixture.

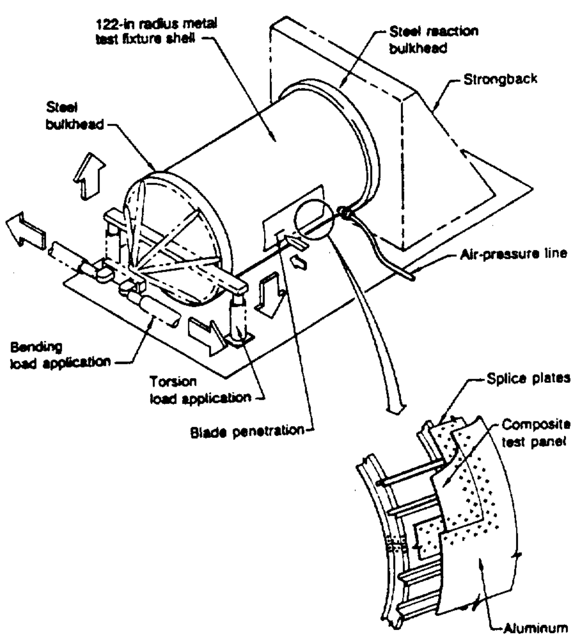

Figure 26. Pressurized Fuselage Damage Containment Tests

Four large panel tests are planned: (1) crown panel, (2) keel panel, (3) crown-to-side longitudinal splice, and (4) keel-to-side longitudinal splice. Each panel will be tested for multiple load conditions and damage scenarios prior to the large penetrating damage event.

SUMMARY

Keel, side, and crown areas of an aft fuselage section directly behind the wing-to-body intersection of a wide body aircraft are used for composite technology development and verification purposes in ATCAS. Boeing Commercial Airplanes Group is the prime contractor for the ATCAS program, with significant contributions also coming from other Boeing Groups, industrial subcontractors, and universities. Initial ATCAS efforts plan to develop composite technology that meet NASA Advanced Composite Technology goals for cost and weight savings, relative to 1995 metals technology. During the final years of the ATCAS program, work tasks are planned to provide the degree of technology verification required to commit to development of a full scale barrel section.

A design build team approach has been established to minimize manufacturing costs and structural weight. Three steps are used by the ATCAS DBT to select, evaluate, and optimize fuselage concepts. First, the DBT selects baseline concepts that appear to have a strong potential for cost and weight savings. This helps to focus early efforts in solving major technical issues. Second, cost and weight savings potential of the baseline and several alternate concepts are evaluated using detailed designs and manufacturing plans. This step has been termed global design optimization because it identifies cost centers associated with fabrication and assembly of the entire structure. Finally, the DBT attempts to reduce significant cost centers associated with the chosen concept. This third step has been termed local optimization because it addresses individual manufacturing steps and subcomponent design within the global cost constraints identified for the entire structure.

Four large quadrant panels (e.g., crown, 2 sides, and keel) were selected to minimize the number of panel splices and to take advantage of a low-cost batch process for fuselage skin layup. A skin panel concept with bonded stringers and frames, was selected for the crown and side quadrant baseline design concepts. Selection of this concept was justified by global design optimization studies for the crown, which indicated cost and weight savings potential. An innovative thick laminate/sandwich concept was selected for the keel panel. This choice was made to avoid anticipated problems with composites in fabricating and splicing a more traditional keel panel design. The major manufacturing and performance issues associated with baseline concepts were identified. Detailed cost estimates for side and keel baseline concepts will be performed in the following year.

All composite crown designs considered in global optimization studies indicated economic advantages over the metal benchmark in cost and weight trades. The most efficient composite crown designs were found to have 50% the weight and equivalent manufacturing costs. Composite concepts were competitive with the metal benchmark primarily because reduced assembly labor offset lower aluminum material costs. Cost savings on the order of 25% were projected for composite crown panels by attacking cost centers (e.g., using tow placed fiberglass/graphite hybrids to reduce material costs) in local optimization studies.

Considerable work was completed in addressing technical issues. A crown design tool that combines manufacturing cost and structural performance constraints with an optimization algorithm is near completion. Panels (e.g., 110 in. stiffened panels and intraply hybrid skin panels) were fabricated to serve multi-purposes in evaluating technical issues such as process feasibility, low-cost tooling concepts, impact damage resistance, and tension damage tolerance. Analysis methods were developed and experimentally verified for toughened composites in support of keel applications. These included post-impact compressive strength prediction. Data bases were obtained for manufacturing and performance evaluation of new material forms, including braided composites and sandwich core. Twenty technical papers, including seven in this proceedings, were published to document ATCAS work completed to date.

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