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COST STUDIES FOR COMMERCIAL FUSELAGE CROWN DESIGNS[1]

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ABSTRACT

Studies were conducted to evaluate the cost and weight potential of advanced composite design concepts in the crown region of a commercial transport. Two designs from each of three design families were developed using an integrated design-build team. A range of design concepts and manufacturing processes were included to allow isolation and comparison of cost centers. Detailed manufacturing/assembly plans were developed as the basis for cost estimates.

Each of the six designs was found to have advantages over the 1995 aluminum benchmark in cost and weight trade studies. Large quadrant panels and cobonded frames were found to save significant assembly labor costs. Comparisons of high- and intermediate-performance fiber systems were made for skin and stringer applications. Advanced tow placement was found to be an efficient process for skin layup. Further analysis revealed attractive processes for stringers and frames. Optimized designs were informally developed for each design family, combining the most attractive concepts and processes within that family. A single optimized design was selected as the most promising, and the potential for further optimization was estimated. Technical issues and barriers were identified.

INTRODUCTION

During the 1970s, high fuel prices dictated a focus on reduced weight in aircraft design. The lower fuel prices in recent years, in conjunction with a highly competitive aircraft marketplace, have forced airframe manufacturers to consider the affordability of weight savings. Past applications of composite materials have demonstrated their ability to reduce weight, but typically at significantly higher costs.

The relative lack of experience with composite materials results in increased risks in both cost and performance. Boeing, therefore, requires potential composite applications to not only have significant weight savings, but also to have costs less than or equal to aluminum alternatives. NASA has also recognized the need for affordability and funded the Advanced Composite Technology (ACT) program, with the objective of developing the technology required for cost-effective application of composite materials to primary aircraft structures. The specific goals of the program are to obtain 25-30% cost savings and 40-50% weight reductions from current airframes for a resized all-composite airframe.

The emphasis of Boeing's Advanced Technology Composites Aircraft Structures (ATCAS) contract, funded under the ACT program, is on pressurized commercial transport fuselages. The approach is to

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develop and demonstrate innovative composite fuselage structural concepts that are cost and weight effective. Boeing selected the fuselage section immediately behind the wing box and main-landing-gear wheel well area for this technology development and verification effort. The 767-X development airplane, targeted for production in 1995, was selected as the metal benchmark to provide a comparison with state-of-the-art aluminum technology.

Recurring labor is a major cost center in metal aircraft structure, due primarily to the low raw material costs. The large amount of assembly required in aluminum structure results in assembly activities accounting for nearly half the recurring labor costs, as shown in Figure 1. This, combined with indications of strong interactions between design details and manufacturing costs, led to a decision to consider assembled structure during concept selection. Manufacturing and cost personnel were included in the design team to ensure these areas were addressed early in the design cycle, where changes have the largest impact. The design-build-team (DBT) process, which is discussed more fully in Reference 1, involves detailed cost- and weight-sensitivity studies (referred to as "global optimization") to determine the best overall design concept. These studies are followed by "local optimization," which includes subcomponent and element tailoring within the selected design concept.

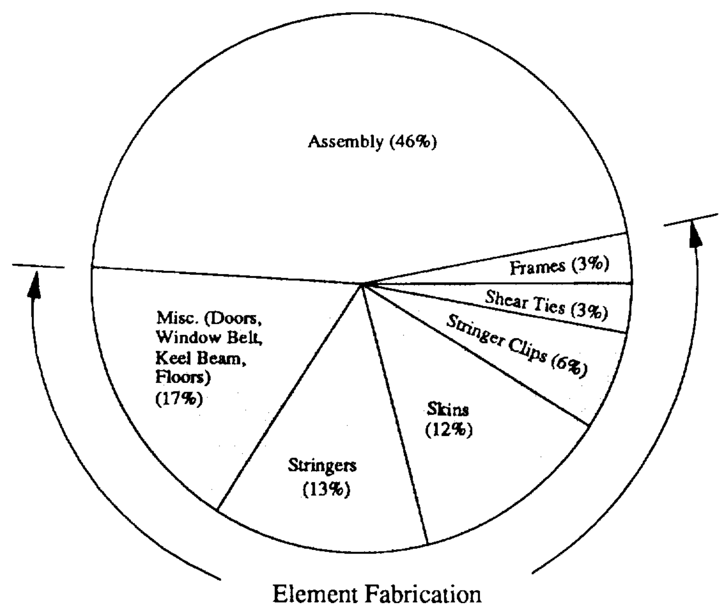

Figure 1: Recurring Labor for a Typical Boeing Metallic Aft-Fuselage

The study section of the fuselage was divided into four quadrant panels: crown, keel, left side, and right side. Each of these panels was treated separately. This paper addresses the detailed cost and weight studies of the global optimization process for the crown quadrant panel, which was accomplished during the period of January 1990 through July 1990.

COSTING PROCESS

An industrial engineering approach was used to develop cost estimates of each design concept. The completed design layouts contained information needed to generate detailed manufacturing plans. These plans defined each individual process required to fabricate and assemble the finished quadrant panel, and the tooling, labor, and recurring material requirements to support each. In-house historical data and vendor-supplied estimates were used to define machine capabilities, process limits, process-based material utilization rates, materials costs and labor for individual operations. Process variables, such as learning curves, and shop variances, were also developed from historical and vendor-supplied data. Detailed costs for each operation were then generated and summed to provide various levels of cost visibility.

In developing manufacturing plans and cost estimates, an automated factory was assumed for definition of equipment and tooling. Reduction of part handling and the combination of operations were significant considerations. Estimates were based on a production run of 300 airplanes at a rate of 5 per month. Costs for materials were based on only this 31 ft. crown panel at these production rates. Labor rates of $100 and $75/hr. were used for recurring and non-recurring labor, respectively; 1995 dollars were used in all cases. Capital equipment costs were not included.

DESIGN DEVELOPMENT

Design Conditions

Designs developed for this study were sized to loading conditions representative of the baseline metallic fuselage. Hoop and axial damage tolerance, Euler stability, and bolted joint strength were all considered. A minimum gage of 10 plies (0.074 in.) was used to minimize repair requirements after severe hail storms.

Predictions of damage tolerance strength were made using a method based on References 2 and 3, and Boeing-internal studies. Analysis of crown configurations using this method indicated that "failsafe" tension damage tolerance conditions are more critical than "ultimate" or "safe-flight" conditions. An axially oriented 8 in. narrow slot in conjunction with a hoop tension loading of 1260 lbs./in. was used for the hoop damage tolerance. A circumferentially oriented 8 in. narrow slot in conjunction with an axial tension load distribution, ranging from 2900 to 3600 lbs./in. on the forward end and from 1400 to 1800 lbs./in. on the aft end, were considered for axial damage tolerance.

"Ultimate" tension loads were used for determining joint strength. The ultimate hoop loading is 2200 lbs./in. The ultimate axial loads range from 5400 to 6800 lbs./in. on the forward end and from 2700 to 3500 lbs./in. on the aft end.

Column stability was determined with ultimate compressive loading. These axial loads range from 2300 to 2700 lbs./in. on the forward end and from 1100 to 1400 lbs./in. on the aft end.

Design Families

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 to 159 during subsequent brainstorming sessions. Schedule constraints would not allow cost and weight evaluations of all concepts. Instead, concepts were classified into eight design families, each having common manufacturing characteristics.

Three of these families are permutation of the skin/stringer/frame concept, with differing amounts of cocuring and cobonding of individual elements. Two families are variations on sandwich construction with circumferential frames. Other families include geodesic stiffening, integrally stiffened skins, and continuous 360° fuselage concepts.

Crown Designs

Three families were selected for consideration in the crown panel studies, based on their perceived potential for cost- and weight-effectiveness. Family B is a traditional skin/stringer/frame geometry, with the stringers cobonded or cocured to the laminate skin. The frames are mechanically attached to the stiffened panel. Family C is also a skin/stringer/frame geometry, with both the stringers and frames cobonded or cocured to the laminate skin. Family D is a sandwich geometry, with cobonded frames to provide hoop stiffening.

Two designs were developed from each of these three families. In developing the concepts, cost-minimization was a major consideration. In addition, a range of concepts for each element (i.e., skins, stringers, frames) was included within and across the design families to isolate costs.

Table 1 itemizes the important features of the two Family B designs. The major differences are (1) the skin and stringer materials, (2) the stringer geometry and fabrication process, and (3) the frame fabrication process. Design B1 uses IM6[2]/3501-6[3] for the skins and drape-formed hat stringers. The frames for this design are compression-molded fabric. Design B2 uses AS4[4]/3501-6 for the skins and pultruded non-tapered blade stringers. The frames are fabricated by resin-transfer-molding (RTMing) braided preforms.

		Design B1	Design B2
Skin	**Mat'l, Form** **Mfg. Process**	IM6/3501-6, Tow Batch Tow-Placement	AS4/3501-6, Tow Batch Tow-Placement
Stringers	**Shape** **Mat'l, Form** **Mfg. Process**	Hat IM6/3501-6, Tape CTLM/Drape Form	Blade AS4/3501-6, Prekitted Tape Pultrusion
Frames	**Shape** **Mat'l, Form** **Mfg. Process**	Z AS4/3501-6, Fabric Compr. Molded	Z AS4/DPL862[5], Braid Batch RTM (4)

Table 1: Major Features of Family B Designs

[2]IM6 is a graphite fiber system produced by Hercules, Inc.

[3]3501-6 is a resin system produced by Hercules, Inc.

[4]AS4 is a graphite fiber system produced by Hercules, Inc.

[5]DPL862 is a resin system produced by Shell Oil Corp.

Table 2 compares the two designs of Family C. The primary variables between the two concepts are (1) the stringer geometry, (2) the frame geometry, and (3) the frame manufacturing process. In Design C1, the hat stringers are constant-height and thickness-tapered. The frames for this design are manufactured using braid/RTM technology, and the frame flanges are bonded to the skin and entire stringer cross section. In Design C2, the hat stringers are constant-thickness and height-tapered. The frames are fabricated from a long discontinuous fiber (LDF[6])/PEKK using a stretch forming operation. The frame flanges bond only to the skin and attached stringer flanges. "Mouse-hole" cutouts in the frame at the stringer-frame intersections allow the stringers to pass through.

		Design C1	Design C2
Skin	**Mat'l, Form** **Mfg. Process**	IM6/3501-6, Tow Batch Tow-Placement	IM6/3501-6, Tow Batch Tow-Placement
Stringers	**Shape** **Mat'l, Form** **Mfg. Process**	Thickness-Tapered Hat IM6/3501-6, Tape CTLM/Drape Form	Height-Tapered Hat IM6/3501-6, Tape CTLM/Drape Form
Frames	**Shape** **Mat'l, Form** **Mfg. Process**	Contoured-Flange J AS4/DPL862, Braid Batch RTM (16)	Mouse-Holed J AS4/PEKK, LDF Stretch Form

Table 2: Major Features of Family C Designs

The major features of the two Family D designs are shown in Table 3. Primary differences include (1) the skin material, (2) the panel edge concept, and (3) the frame manufacturing process. Design D1 features AS4/3501-6 skins, with a ramped-down panel edge. The frames for this design are fabricated using braid/RTM techniques. IM6/3501-6 is used for Design D2 skins. A square-edge panel concept is employed, and the frames are manufactured using a dry-fiber pultrusion process.

		Design D1	Design D2
Skin	**Mat'l, Form** **Mfg. Process**	AS4/3501-6, Tow Batch Tow-Placement	IM6/3501-6, Tow Batch Tow-Placement
Core	**Shape** **Form** **Thick., Density**	Ramped-Edge Aramid Honeycomb 0.5 in., 4 lb./ft^3	Square-Edge Aramid Honeycomb 0.5 in., 4 lb./ft^3
Frames	**Shape** **Mat'l, Form** **Mfg. Process**	J AS4/DPL862, Braid Batch RTM (2)	J AS4/3501-6, Raw Mat'ls Dry-Fiber Pultrusion

Table 3: Major Features of Family D Designs

[6]LDF is a trademark of E. I. du Pont de Nemours & Co.

RESULTS

From the design studies conducted, several generalizations can be made concerning design drivers. Tension failsafe damage tolerance controls the majority of the panel in all designs. Stringer thicknesses are determined by Euler stability considerations. Skin and stringer thicknesses at the edges of the panels are controlled by the fastener bearing requirements. Minimum gage requirements affect the skin thicknesses near the aft (lightly-loaded) end of the panels.

Figure 2 illustrates the approximate weight breakdown observed in the six design concepts. The stiffened panel (skin and stringers, or sandwich panel) accounts for 70 to 80% of the total crown quadrant weight. In the skin/stringer designs, the skin is approximately 50% of the total, and the stringers 20%. In both concepts, frames account for 10 to 15%, and the splices 5 to 10% of the total weight.

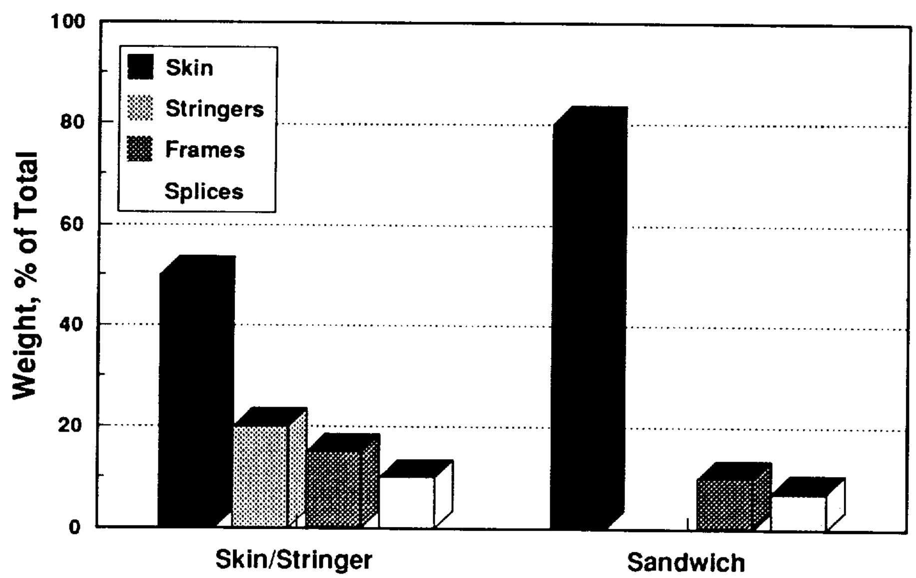

Figure 2: Approximate Weight Breakdown of Crown Designs

Figures 3 through 5 illustrate cost results specific to Design C1, but they reflect trends inherent to all the designs. The relationship between recurring and nonrecurring costs are shown in Figure 3. Recurring costs comprise approximately 75% of the total costs and are divided nearly equally between material and labor.

In Figure 4, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. About half of the nonrecurring costs are related to element fabrication (e.g., skins, stringers, frames, etc.), with costs relating to bonding and assembly operations comprising the other half. In contrast, approximately 70% of the recurring costs are related to element fabrication, with the remainder related to bonding and assembly operations.

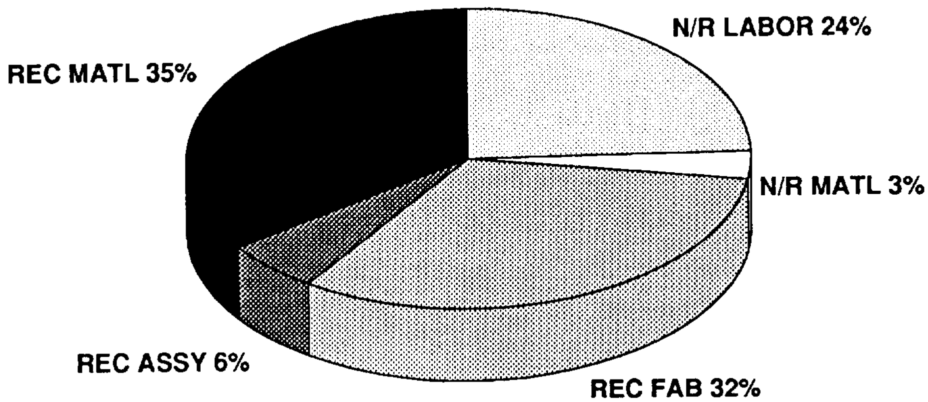

Figure 3: Recurring and Nonrecurring Costs of Design C1

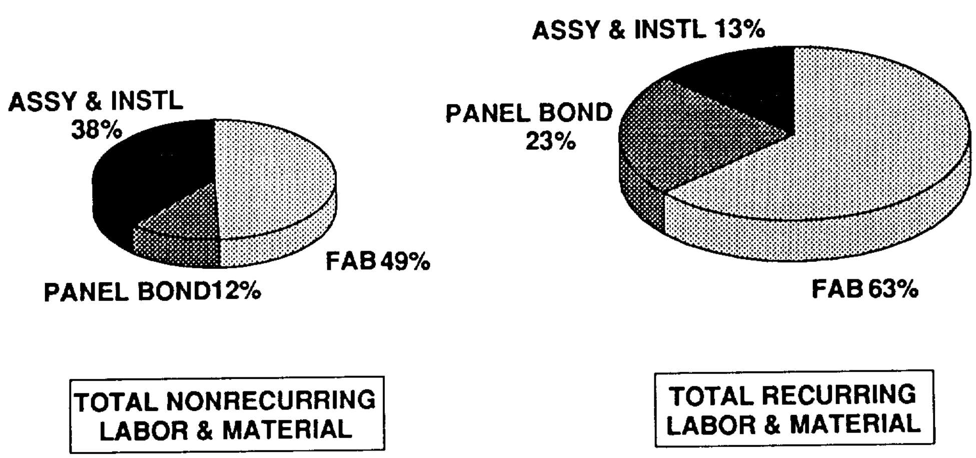

Figure 4: Breakdown of Recurring and Nonrecurring Costs of Design C1

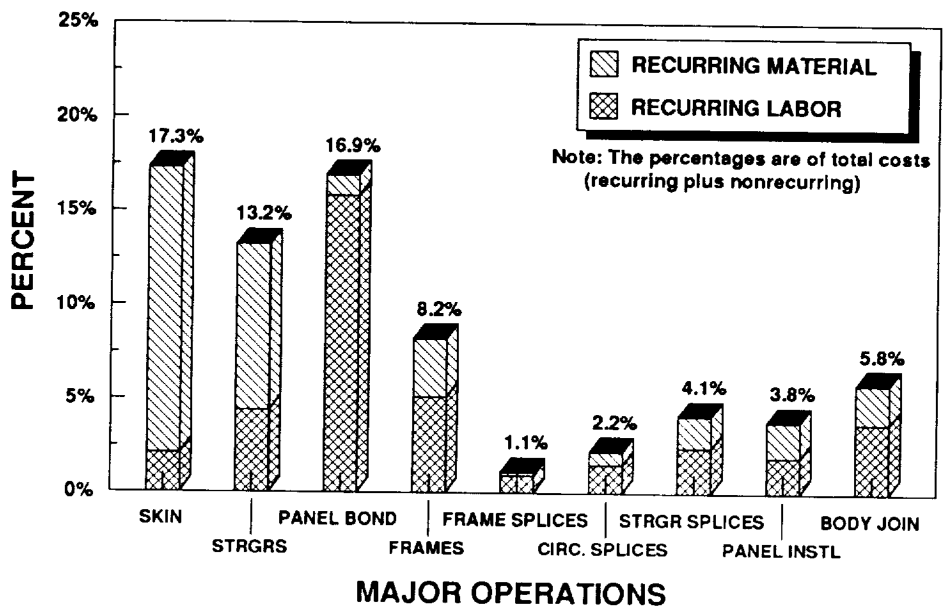

Figure 5: Design C1 Recurring Costs by Major Operation

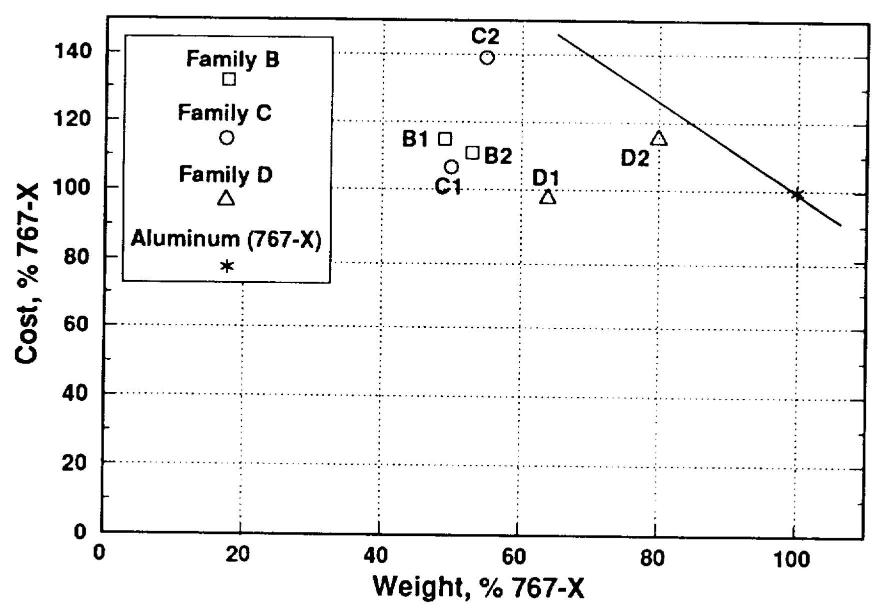

Figure 6: Crown Design Cost/Weight Results

The recurring material and labor costs for each major manufacturing step are shown in Figure 5. The most significant recurring cost centers are (1) the fabrication of the skin, stringers and frames; (2) the panel bonding operation; and (3) fasteners required for installation.

A comparison of the cost/weight results, normalized to that of the 767-X aluminum baseline, is contained in Figure 6. The costs, in general, are within 100 to 120% of the baseline value, with Design C2 being the notable exception. The skin/stringer concept weights are approximately 50 to 60% of the baseline, with the two sandwich concepts (i.e., Designs D1 and D2) being somewhat higher.

The sloped line through the 767-X baseline point in Figure 6 represents a typical performance value of weight. This value is the amount that customers are willing to pay for reduced weight, and therefore is a measure of the life cycle costs of this weight. All designs falling on a single line parallel to this are of equal value. Those designs falling below this line are more desirable, and those falling above, less desirable. As shown, all composite concepts, although not optimized, are more attractive than the aluminum baseline. Note that two of the designs (i.e., Designs C2 and D2) are less attractive than the other four composite designs.

ANALYSIS OF RESULTS

Cost Comparisons

As shown in Figure 2, structural weight is dominated by that of the skin. All designs studied used advanced tow placement and a quadrant panel batch process to layup the skin plies (see Ref. 1). This process was found to be cost efficient in several ways. First, large quadrant panels minimize labor costs for final assembly (see costs for panel installation and body join in Figure 4). As shown in Figure 1, assembly labor is significant for metal structure. Another advantage to advanced tow placement in a batch quadrant process is the relatively low percentage of recurring labor costs. Finally, prepreg tow is projected to be a low-cost material form in 1995 (e.g., \$25/lb. for AS4/3501-6 tow prepreg).

Since the stiffened panel is a major cost and weight center, the impact of the fiber system used in these locations is of extreme interest. In all designs, either AS4/3501-6 or IM6/3501-6 material was used for the skins and stringers. An analysis of the cost trends involved in replacing IM6 fibers with AS4 is shown in Figure 7. The bars in this graph show the ratio of AS4 to IM6, with the adjacent bars addressing the behavior observed in the skins and the stringers. The lower performance of the AS4 fiber system results in a 10 to 15% weight penalty due to added material. However, the cost per pound of the AS4 is significantly lower, ranging from 55 to 65%, depending on the material form (i.e., tow or tape). The final material-cost ratio is the product of these two values, and is in the 70% range. Additional recurring labor costs, which are incurred due to the increased number of plies, are not included in this analysis. However, even when they are included, the cost advantages of AS4 clearly outweigh its performance penalty, for these applications. A performance value of weight in excess of \$130/lb. would be required to select the IM6 system, significantly higher than normal values.

Similar results are seen in an analysis of the sandwich designs. In Design D1 and D2, a hard (0°-dominated) AS4 concept and a soft IM6 (±45°-dominated) concept are used, respectively. Additional studies of soft AS4 and hard IM6 concepts indicate that, while the hard concept is slightly more cost effective than the soft concept, the large cost reductions are gained by changing to the less expensive AS4 system.

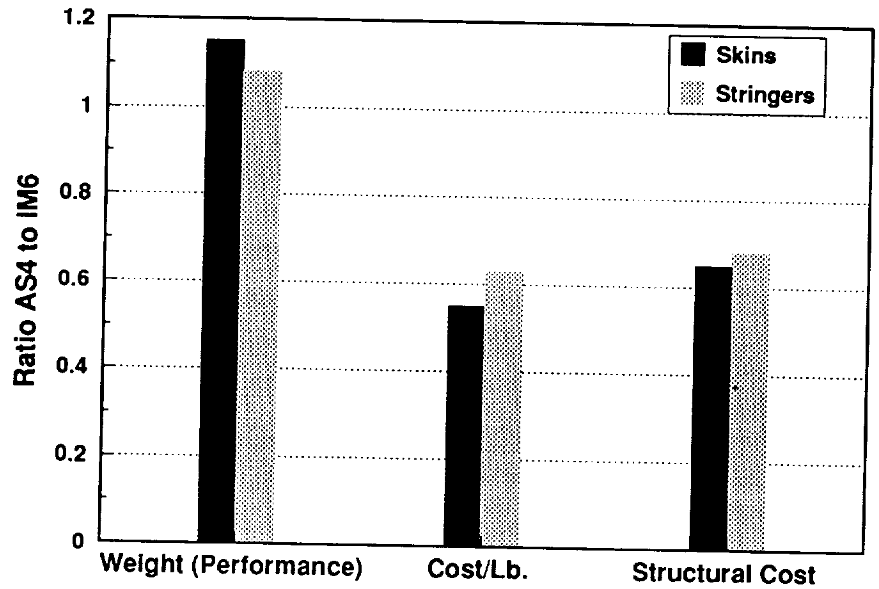

Figure 7: Comparison of AS4 and IM6 Fiber Systems

A comparison of stringer fabrication processes is contained in Figure 8, which illustrates the costs per pound of each stringer design. The pultrusion process used on the Design B2 blade stringers results in cost of \$175/lb. primarily due to the cost of the prekitted prepreg material form. The hot-drape-formed hat stringers of Designs B1, C1, and C2, are less costly on a per pound basis (≈ \$110/lb.), although recurring labor was higher than the pultrusion process. In a modified Design B1, where AS4 material is substituted for IM6 (including additional plies to meet the performance requirements), the cost per pound is reduced to approximately \$75/lb.

Several interesting conclusions result from this comparison. First, the pultrusion process is inherently more efficient than tape laminating with hot-drape-forming, but the material costs must be reduced to approximately \$30 to \$40/lb. for the end product to be a viable option. This suggests that dry fibers with an in-line resin wetting process is likely required. Secondly, material is a major cost center in stringer fabrication. Further reductions could possibly be obtained for the drape-formed stringers by switching from a tape form to prepreg tow in fabricating flat charges for draping.

The frame manufacturing process used for each design is the primary variable for which costs can be isolated. Costs per pound are shown in Figure 9. The stretch-formed LDF (Design C2) and the compression-molded fabric (Design B1) designs both result in relatively high costs (\$212 and \$170/lb., respectively). The LDF frames are purchased as finished parts, so their costs are considered as recurring material costs. Because of this, the major cost centers of this process cannot be identified. High recurring labor costs for the compression-molded fabric frame are due to hand layup of the fabric charges. The costs per pound of batch processed braided/RTM frames exhibit a considerable range. This is attributed to the number of frames in a batch process, with the costs reducing from \$160 to \$90/lb. as the quantity of frames fabricated in a single operation increase from 2 to 16. The \$126/lb. costs of the dry-fiber pultrusion concept (Design D2) is lower than all other concepts, except the 16-at-a-time batch RTM process.

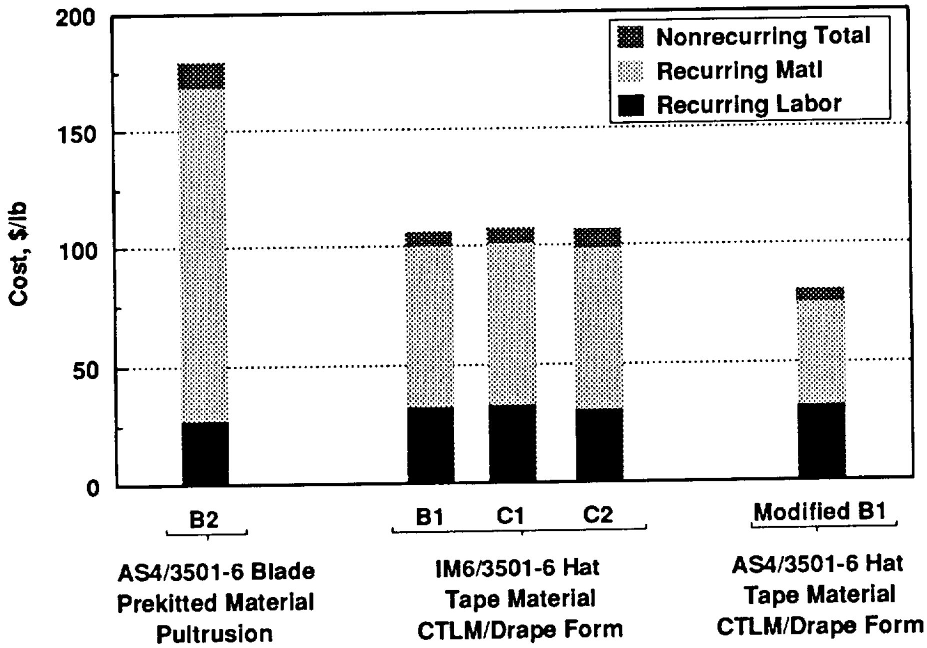

Figure 8: Cost Comparison of Stringer Fabrication Processes

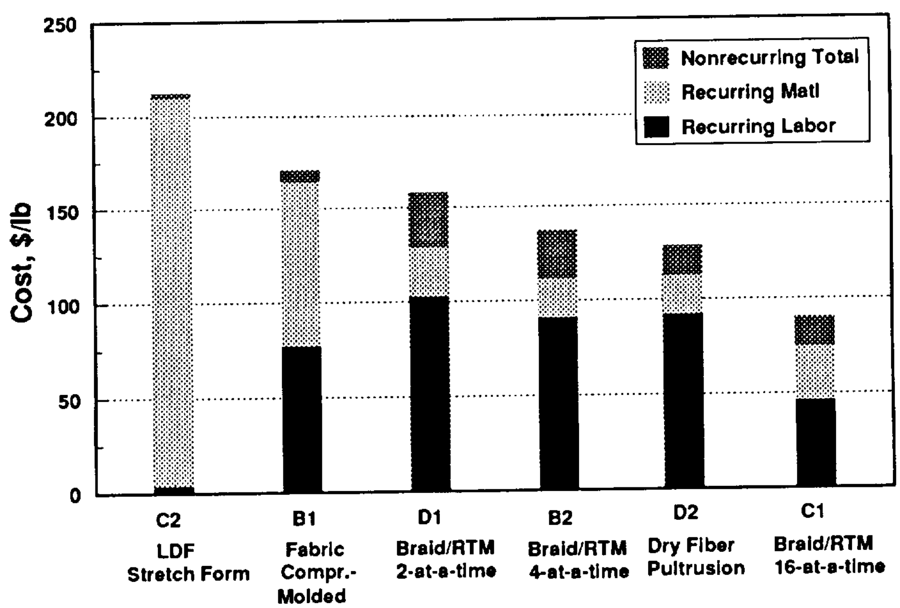

Figure 9: Cost Comparison of Frame Fabrication Processes

Global Optimization

After understanding the cost estimates derived for individual design concepts, an "optimum" design within each family was developed. Efficient materials, fabrication process, and element design concepts that are included in the six designs described above, were combined to provide the most cost- and weight-efficient crown panels for each design family. This process was significantly less formalized than the original cost estimates but was necessary to provide a basis for determining the best design.

The globally optimized Family B design is primarily the hat-stiffened concept from Design B1. The skins, stringers, skin splices and stringer splices are all converted to AS4/3501-6. The thickness of the skins and stringers are increased by 2 plies and 1 ply, respectively, to maintain adequate damage tolerance. The braided/RTM Z-section frames from Design B2 are used, although it is assumed that the frames are RTMed 16-at-a-time. The results of the study show that this design concept is 98% of the cost of 767-X baseline concept and 54% of the weight.

The globally optimized Family C design is a slight modification of the continuously bonded frame concept of Design C1. The skin, stringer, and associated splice materials are converted to AS4/3501-6, with 2 plies and 1 ply being added to the skin and stringers, respectively, for damage tolerance requirements. The J-section frame with the contoured outer flange is maintained without modification, since it already assumes an RTM batch process of 16-at-a-time. The results of the study show that this design concept is 99% of the cost of 767-X baseline concept and 55% of the weight, nearly identical to those for the globally optimized Family B design.

The globally optimized Family D design is close to that of Design D1. The only modification is the cost-efficient frame batch process that RTMs 16 frames in one process. The skins are a hard AS4/3501-6 concept. The ramped edge of the quadrant panel is maintained, although it has not been established as clearly superior to the square-edge design. The results of the study show that this design concept is 94% of the cost of 767-X baseline concept and 64% of the weight.

Selection Rationale

The cost and weight results of the globally optimized designs for each family are shown in Figure 10 with the original results. The Family B and C costs and weights are nearly identical, both being approximately equal in cost and 50% of the weight of the 767-X. The sandwich design (Family D) is slightly less costly, yet significantly heavier than either of Families B or C. The sloped line through the Family B and C designs reflects a typical performance value of weight. When this is considered, Family D is clearly not an optimum design concept.

For all concepts, damage tolerance requirements control much of the design. It was therefore a major consideration in choosing the baseline crown concept for further development in local optimization. In all designs, it is assumed, based on limited existing data, that additional skin padding (i.e., tear straps) are not required for tension damage tolerance. Since longitudinally oriented cracks appear to be the more critical condition, the Family B concept seems to be at most risk from this assumption. Families C and D have integrally bonded frame flanges to provide some crack stopping capability, where Family B has no such features. Family D design appears to be at least risk, since the sandwich construction increases the local bending stiffness at the crack tip, which in turn reduces the localized bending stresses. Significantly higher strengths are realized in sandwich construction for pressure loads with the 8 in. crack size considered for the failsafe condition.

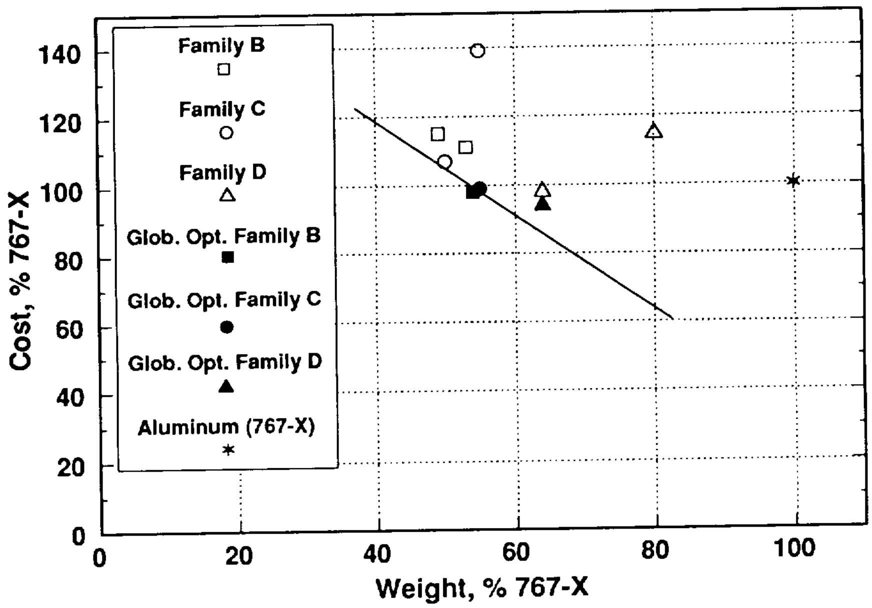

Figure 10: Globally Optimized Designs

Manufacturing risk was also a significant consideration in selecting the baseline concept. Family B has the lowest perceived risk, since manufacturability of a mechanically fastened concept has been previously demonstrated, although on wing/empennage-type structure. The Family C manufacturing risk was judged to be the highest. Both Families C and D carry substantial risk associated with joining very large, stiff sections to other quadrants and to other body segments. High local stresses can be induced by forcing compatibility between warped panels. The overall stiffness of these built-up designs magnifies the localization of these high stresses. The Family C design, however, has additional complexity of splicing the stringers at the body-join operation. Maintaining the very small locational tolerances required for these splices at both ends of a very long panel adds additional risk.

Family C was selected as the baseline crown concept. It demonstrates excellent cost/weight performance, clearly superior to Family D. Its manufacturing risk was judged to be higher than that of Family B, but it also carries significantly less performance (i.e. damage tolerance) risk.

Due to damage tolerance uncertainties in both Families B and C, Family D was selected as a backup to the baseline. This provides a fall-back position if the apparent cost/weight performance erodes as additional data on damage tolerance becomes available, or if the manufacturing concerns of Family C cannot be overcome.

Local Optimization Potential

The local optimization process provides the opportunity to further refine the selected concept within the cost constraints defined by global optimization. Material, geometric and laminate variables affecting cost and weight are considered in the local optimization, as well as improvements in the manufacturing processes. An effort was made to evaluate the magnitude of the potential cost/weight changes that might occur during that process.

The use of less costly materials will be assessed, especially in the skins and stringers, where the majority of material resides. Fiberglass, which exhibits a very large strain-to-failure, appears attractive as a low-cost material for use in the skins and stringer flanges, where tension damage tolerance is an important consideration. Intraply hybrid concepts using S-glass and AS4 material could provide similar residual strength as compared to an all AS4 concept, resulting in a cost savings and a weight increase. This intraply hybrid concept is also ideally suited for the efficient tow-placement process. Other reductions in material cost may be realized by using dry-fiber pultrusion processes in the stringers, and by tow placing the stringer charges for hot-drape-forming.

Major geometric variables to be considered include stringer spacing, frame spacing, stringer height and width, and frame height and width. Major laminate variables include ply orientations and stacking sequences. A software design tool that incorporates cost and structural mechanics constraints with an optimization algorithm is being developed to support studies on the effects of material, geometric, and laminate variables.

Several manufacturing improvements provide opportunities for cost savings. Tow placement efficiency rates can be increased by simply enlarging the current band width or using multiple tow placement heads. These technologies are considered to be low risk and could conceivably increase rates up to 100%. A major cost center is the process for locating and bagging the quadrant assembly for subsequent curing. The technology of form-fit reusable bagging offers significant cost savings by reducing locating-tooling, recurring material costs, rejection rate, and assembly/bagging labor.

Panel splicing provides additional opportunities for improving both cost and weight. Composite fasteners and rivets may be able to reduce the recurring fastener costs. Stringer splicing at the fore and aft ends of the quadrant is also a major concern for Family C. Splice concepts that do not require precise stringer alignment are attractive as a method of reducing the cost and risk in this area.

The potential cost and weight improvements in the local optimization process are shown in Figure 11, along with similar potential for the aluminum baseline design. These aluminum improvements relate primarily to breakthroughs in assembly technology, including high-speed robotic fastening. The broader width of the composite potential is an indication of the wider range of materials and other variables available in the local optimization process. The cost-reduction potential appears to be significantly greater for the composite design than for the aluminum baseline.

TECHNICAL ISSUES AND BARRIERS

The most critical manufacturing issue associated with both the Family C (skin/stringer, bonded frame) and Family D (sandwich) concepts is the effect of locational tolerances and panel warpage on final assembly. Quadrant panel designs have high local stiffness due to bonded stringers/frames or sandwich construction. This stiffness magnifies panel fitup and stringer splicing difficulties.

Another critical manufacturing issue is the control of fabrication processes to yield quadrant panels of acceptable quality. Quadrant panel cost benefits assume that large panels will not be rejected due to manufacturing defects. Further refinement of the designs will include robust designs and processes which minimize potential problems due to fabrication anomalies.

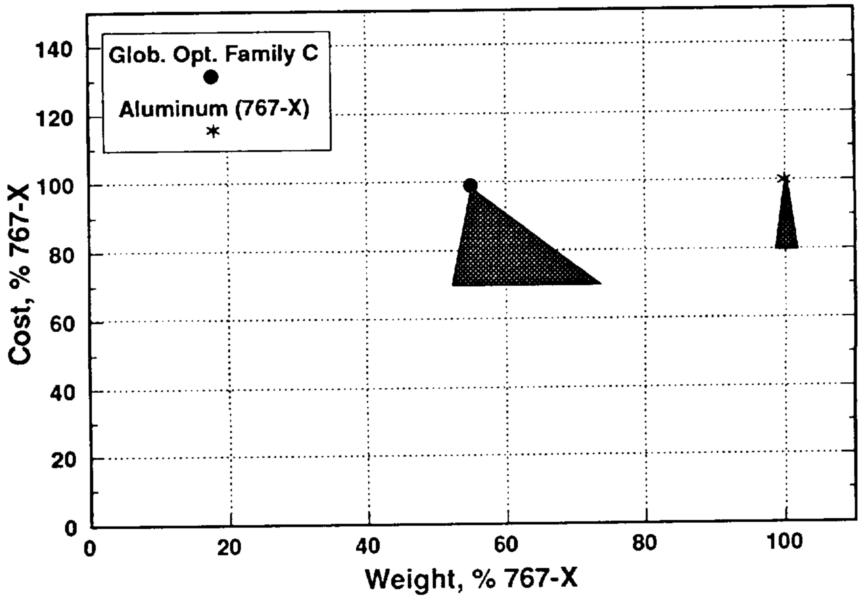

Figure 11: Local Optimization Potential

Several critical performance issues require further understanding to ensure adequate performance and properly refine the design. These include:

1. *Hoop tension damage tolerance of panels with large penetrations*. The most critical damage geometries for hoop loading are expected to be slender notches oriented along the longitudinal axis (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. *Axial tension damage tolerance of panels with large penetrations*. The critical damage geometries for axial loads are expected to be slender notches oriented along the circumferential axis and severing a stringer. Both hoop and axial tension damage tolerance in the crown are expected to yield lower strengths for unidirectional loading cases since the Poisson effect reduces ply stresses for the biaxial tension case (Reference 4). However, the complex stress distribution near a hard point could be most severe.

3. *Axial compression stability of panels with and without damage*. Euler stability and post-buckled performance of the panel must be demonstrated with and without damage.

4. *Minimum skin gage required to satisfy hail impact criteria*. Structural tailoring in the crown is limited by the minimum skin thickness requirement used to suppress visible damage due to severe hail storm conditions.

5. *Fiber/resin distribution of frames after RTM processing*. The performance, warpage, and dimensional tolerance control of complex geometries such as curved frames is expected to relate to fiber/resin distribution. Cost efficient methods of controlling the quality of RTM parts must be established.

6. *Performance of the stringer/frame intersection*. The intricate bond concept, with the frame bonded to the entire stringer cross section, requires precise alignment of all parts. The mouse-

hole concept alleviates some of the alignment concerns, but adds an additional stress concentration in the frame. Sufficient damage tolerance for skin penetrations located near the intersection must also be established.

7. *Durability of design details (cobonded frames and mechanically fastened splices).* Cyclic pressure load conditions are expected to drive the design of frame-to-skin adhesive joints in the crown. Creep/fatigue interactions must be addressed. Potential bond-surface contamination, resulting from poor handling, can also affect the durability of the frame-to-skin bond. Combined cyclic load conditions also pose a significant problem for longitudinal and circumferential mechanically fastened joints. The effects of environment and real time on damage accumulating in material surrounding the bolt hole will need to be considered.

CONCLUSIONS

Several conclusions can be drawn from the above studies. First, and most important, composite designs can be developed for fuselage crown applications that are significantly more attractive, from a cost and weight perspective, than current aluminum concepts. Composite designs that are approximately equal in cost and half of the weight of aluminum designs are possible.

Recurring costs account for approximately three-fourths of the total crown panel costs, with material splitting this amount nearly equally with fabrication and assembly labor. Element fabrication (i.e. skins, stringers, frames), panel bonding, and fastener costs are the major recurring cost centers.

Batch advanced tow placement layup of quadrant skin panels was found to be cost-efficient for all designs studied. Large quadrant panels minimized assembly labor costs by reducing the number of splices; however, manufacturing concerns about panel warpage and element locational tolerances need to be addressed in future work.

In the crown applications considered, high performance fibers, such as IM6, do not appear to justify their increased cost when compared with intermediate performance fibers, such as AS4. This conclusion cannot be generalized to other applications.

Drape forming of flat uncured charges appears to be an efficient method of stringer fabrication. Automated methods to create the flat charges from either tape or tow are important. Pultrusion also appears attractive for stringer fabrication, but only using a dry-fiber method.

Resin-transfer-molding of braided preforms is an effective method for fabricating body frames. Batch-RTMing provides significant cost advantages as the number of frames per operation increases. Dry-fiber pultrusion also has potential for this type of structure.

A stiffened panel design concept with cobonded frames was selected for future studies that address additional cost and weight savings. The local optimization potential of this design was judged to be greater than that of aluminum designs. This relates to the larger number of composite design variables and the relative maturity of aluminum technology.

Damage tolerance is the primary technical issue to be resolved for crown applications. Several issues required further understanding to ensure adequate structural performance and allow proper optimization. These issues include bonded and bolted joint durability, panel stability with large damage, and the effects of fiber-resin distribution in RTM parts.

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