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GLOBAL COST AND WEIGHT EVALUATION OF FUSELAGE KEEL DESIGN CONCEPTS

517-05

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ABSTRACT

The Boeing program entitled Advanced Technology Composite Aircraft Structure (ATCAS) is focused on the application of affordable composite technology to pressurized fuselage structure of future aircraft. As part of this effort, a design study was conducted on the keel section of the aft fuselage. A design build team (DBT) approach was used to identify and evaluate several design concepts which incorporated different material systems, fabrication processes, structural configurations, and subassembly details. The design concepts were developed in sufficient detail to accurately assess their potential for cost and weight savings as compared with a metal baseline representing current wide body technology. The cost and weight results, along with an appraisal of performance and producibility risks, are used to identify a globally optimized keel design; one which offers the most promising cost and weight advantages over metal construction. Lastly, an assessment is given of the potential for further cost and weight reductions of the selected keel design during local optimization.

INTRODUCTION

The objective of Boeing's Advanced Technology Composite Aircraft Structure (ATCAS) program[1] is to develop an integrated technology and demonstrate a confidence level that permits the cost- and weight-effective use of advanced composite materials in primary structures of future aircraft. The emphasis of the program is on pressurized fuselages. The specific emphasis of the work documented in this paper is on the keel section of the aft fuselage.

A design study of the keel was conducted such that several different concepts were developed in sufficient detail to yield accurate cost and weight estimates. Fabrication and assembly plans were considered early in design development as they have proven to be major cost centers (Reference 1). The composite concepts are compared against a 1995 metallic baseline. The design envelope (i.e., size, loads, and configuration constraints) corresponds to an aft fuselage section (referred to as "Section 46") of an aircraft with a diameter of 244 inches. The loads are characteristic of a commercial aircraft which is 80% the size of a 747.

The ATCAS program utilizes a three step design process which is described in detail in Reference 1. The first step is the selection of a "baseline" concept for each area of the fuselage: crown, side panels, and keel. The

1 This work was funded by Contract NAS1-18889, under the direction of J.G. Davis and W.T. Freeman of NASA Langley Research Center.

selected baseline concepts are those judged to have the greatest potential for cost and weight savings, combined with an acceptable risk.

The second design step is "global optimization" in which preliminary designs are developed in sufficient detail to determine significant cost and weight differences between the baseline concepts and other potentially low-cost/low-weight concepts, as well as the aluminum counterpart. A cost and weight analysis is performed for each different concept. New concepts are then generated within each design family by trading design features in different combinations, leading to the identification of a "best" design for each family, and an understanding of which design details most significantly influence its cost and weight. The cost and weight results, as well as an assessment of the risks associated with each concept, contribute to the selection of a globally optimized design. The completed efforts of the global optimization step, as they relate to the keel, are reported in this paper.

The third step, termed "local optimization," takes the most attractive design from step 2 and optimizes individual design elements (e.g., skin, core, frame, floor beam, etc.), while continually evaluating how changes to the design impact cost centers in a global sense. Local optimization of the keel quadrant had only just begun at the time of this writing; however, based on a review of the results from global evaluation, some of the potential cost and weight savings which could be realized during local optimization have been identified and are included.

Note that the term "design family" refers to a group of design concepts sharing similar geometry, structural performance, and manufacturing cost characteristics. The design families considered in the ATCAS studies have been previously reported (Reference 1). Use of design families provides an efficient method of performing cost and weight trade studies.

DESIGN CONDITIONS

Keel Quadrant Definition

The subject of this design study is the keel quadrant of Section 46 of a wide body airplane — one which has a fuselage diameter of 244 inches and is approximately 80% the size of a 747. Section 46 is the area of pressurized fuselage just aft of the wing-to-body intersection.

The fuselage cross section is divided into four quadrants as a baseline for the ATCAS program (Figure 1). The keel comprises the lower quadrant. The keel quadrant is relatively small due to a configuration constraint imposed by a cargo door on the right side. The stiffened skin, frames, splices, and cargo floor support structure associated with the keel are all included as part of the design trades discussed herein.

Loads

The critical load case for the keel panel is a flight maneuver which causes body bending and puts the keel in compression. The resulting loads are multiplied by a factor of 1.5 to an ULTIMATE condition. The compression load is introduced into the forward end of the keel section as a concentrated force as the loads are carried around the large cutouts which accommodate the wing center section and wheel well (Figure 2). Typical aluminum designs carry these concentrated loads through two massive keel beams, or chords, which are mechanically attached to the stiffened keel skin. The concentrated load is transferred rapidly from the keel beams into the stiffened skin and then sheared out into the rest of the panel. The resulting keel skin compression and shear load contours are shown in Figures 3a and 3b, respectively. The figures show the axial load levels increasing rapidly at the forward end of the panel as the skin picks up load from the keel beams, then leveling off and gradually decreasing toward the aft end. The highest shear loads are in evidence in the areas adjacent to the forward end of the keel beams. Note also the jump in loads in the area near the side panel cargo door opening.

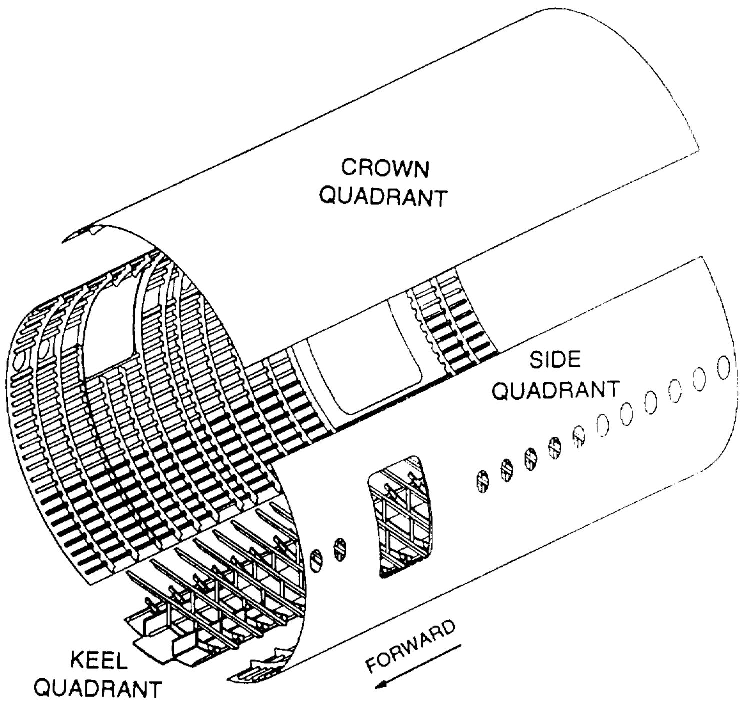

Figure 1: Exploded View of Fuselage Quadrants

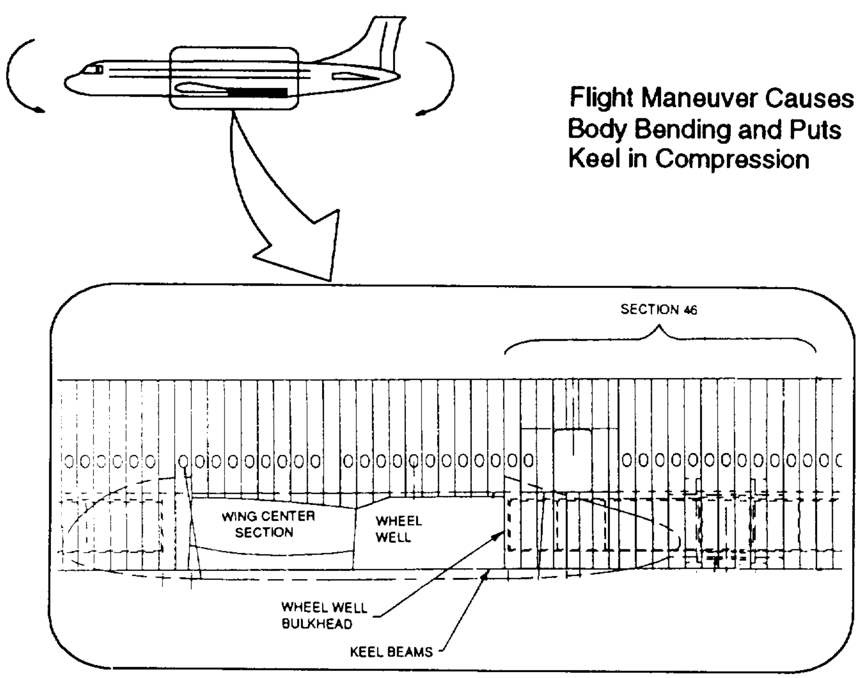

Figure 2: Load Paths in Keel Panel

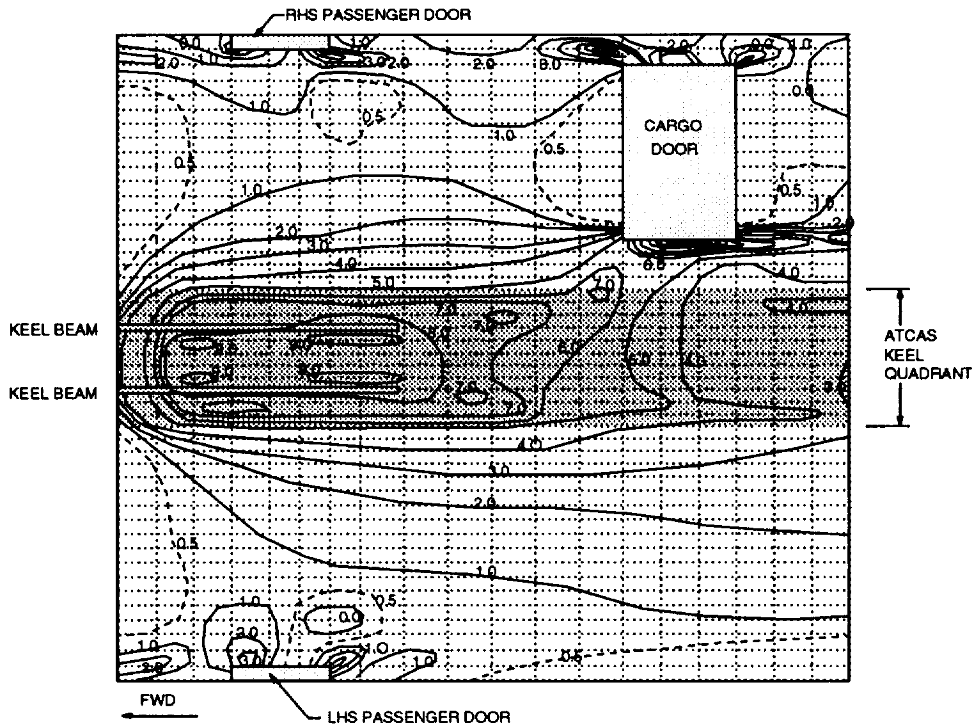

**Figure 3a: Keel Panel Compression Loads (k/in)
(discrete keel beam loads not included)**

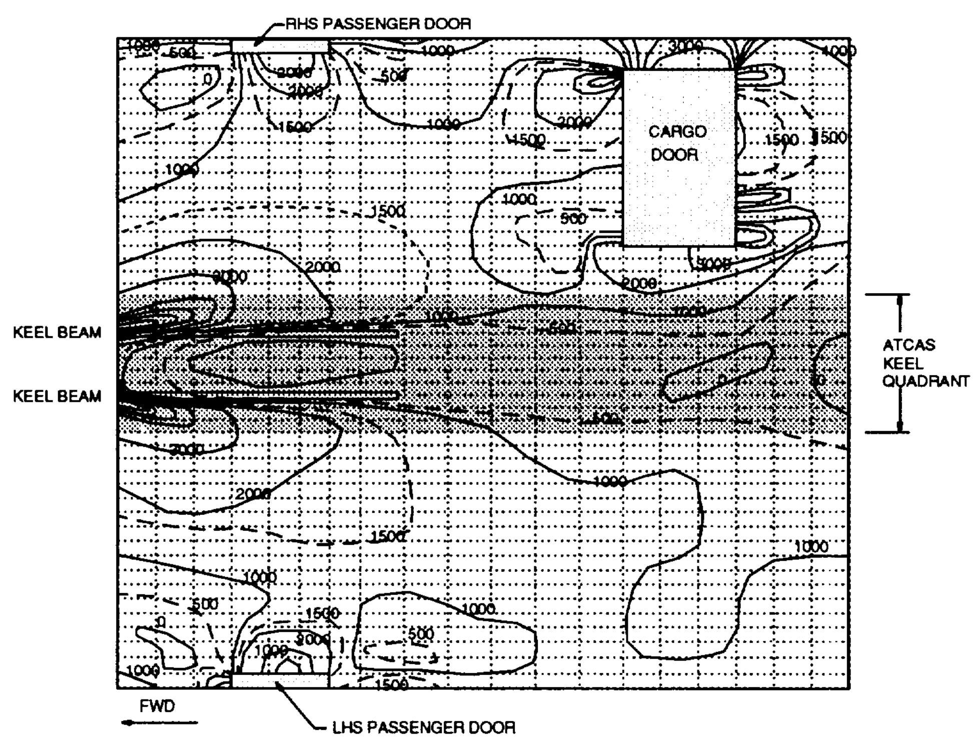

Figure 3b: Keel Panel Shear Loads (lb/in)

The compression load case discussed above is without internal pressure. The same maneuver with flight pressure, although it calls for reduced allowable strains due to the presence of hoop tension, is generally not critical for the keel panel since the axial compression loads are also reduced by the bulkhead pressure. However, an additional load case of ULTIMATE pressure (18.2 psi) acting alone was considered in the design of the keel in the circumferential or hoop direction, particularly with respect to the longitudinal splice joints. ULTIMATE pressure represents two times the maximum positive pressure differential and corresponds to a hoop direction line load of 2220 lb/in for a fuselage with a 122" radius.

Two FAILSAFE tension load conditions were checked for residual strength requirements in a damaged skin panel. The first is equal to 80% of the LIMIT axial tension load and is applied to a panel with a transverse through penetration across one stringer. (The LIMIT axial tension load is obtained by assuming a 40% reversal of the maximum compression load.) The second FAILSAFE condition is a pressure load acting on a panel with a through penetration across one frame, perpendicular to the hoop loading direction. For this damage state, an internal pressure equal to the differential operating pressure plus the aerodynamic pressure times a 1.15 safety factor is applied, resulting in an applied internal pressure of 10.3 psi and a hoop direction line load of 1260 lb/in.

Several load cases were checked in sizing the frames, including ULTIMATE pressure (18.2 psi), flight loads, and a crash condition. Each of the flight load cases was also evaluated when combined with a 13.65 psi pressure load (75% ultimate pressure, or 1.5 x maximum positive pressure differential). A flight load case was used to size the cargo support structure which carries loads from the roller trays supporting the cargo containers.

Material Considerations

A number of different material systems were considered for the trades of the keel panel designs. Two fiber types were considered: high stiffness IM6[2] and low cost AS4[3]. Similarly, the lower cost of 3501-6[4] untoughened resin was traded against the improved compressive performance of the toughened 977-2[5] resin. The need for local stress redistribution in the keel skins favored the use of high resin content systems, despite the resulting sacrifice of stiffness as compared with lower resin content materials (Reference 2). In the Family D sandwich structures, both Rohacell[6] foam and graphite honeycomb core materials were considered.

Structural Criteria

The keel panel was sized to preliminary design cutoff strains which were derived based on ULTIMATE and FAILSAFE damage scenarios. Actual strain values are a function of the laminate thickness and the specific material system employed. For the gages and materials used in the keel panel, the design compression strains ranged from about .0037 to .0048.

The keel panel is also required to be tension damage tolerant. In the hoop direction the structure must show good for cabin pressure with a through penetration damage that includes one frame and adjacent skin bays severed. It must also show good for 80% limit axial tension load with a through penetration that includes one stringer and adjacent skin bays severed.

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

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

[4] 3501-6 is a resin system produced by Hercules, Inc. For the purposes of this study, its properties were assumed to be equivalent to those of the 938 resin system produced by ICI/Fiberite.

[5] 977-2 is a resin system produced by ICI/Fiberite.

[6] Rohacell is a foam core produced by Rohm Tech.

In order to preserve handling qualities and passenger ride comfort, limits have been placed on the overall fuselage bending and torsional stiffness. These translate into axial (EA) and shear (Gt) stiffness requirements for each portion of the complete fuselage barrel, including the keel panel. The current minimum requirement is established as 90% of the stiffness of the baseline aluminum structure.

The minimum margin of safety against buckling is set at 20% to account for uncertainties such as initial imperfections. Wide column stability of stringers and post-buckled skin is based on an effective width approach, with the column length defined by the frame spacing. Initial buckling of the skin between stringers is not allowed to occur below 40% of ultimate load. Additionally, the maximum Poisson ratio mismatch at the skin/stringer and skin/frame interfaces is limited to 0.15 to help prevent stringer and/or frame pop-off.

In sizing the frames, the assumed effective skin width is the full 21 inches (frame spacing) for 18.2 psi pressure acting alone and for 13.65 psi combined with flight loads. This is because the skin is in hoop tension for pressure cases and buckling won't occur. For flight loads without the pressure, only 5 inches of the skin (including that under frame flange) is assumed effective.

DESIGN STUDIES

Background

Two keel panel designs were developed for each of two design families (C and D). Family C is a skin/stringer/frame geometry with both stringers and frames cobonded or cocured to the laminate skin. Family D (the baseline concept for the keel) is a sandwich geometry with cobonded frames to provide hoop stiffening. All designs were developed using the design build team (DBT) approach (Ref. 1), whereby design decisions are based on the input of all pertinent disciplines (e.g., design, manufacturing, cost analysis, materials, structures, quality control).

For each design a comprehensive fabrication and assembly plan was developed to provide sufficient detail for accurate cost estimates. The assumptions used in generating the cost estimates should be noted, as they are important in understanding the relationships between design and cost. The first ground rule calls for a production rate of 5 shipsets per month with non-recurring costs burdened over 300 shipsets. The second ground rule establishes a $100/hr wrap rate for recurring labor and $75/hr for non-recurring labor. All labor, tooling, and material estimates are expressed in 1995 dollars, and material order quantities are based on the Section 46 keel panel only. The estimates are the result of a step-by-step appraisal of the process sequence interaction with each design detail. Important cost drivers such as machine capabilities, process limits, material utilization rates, rate tooling, learning curves, and shop variance were all included in the estimates. It should be noted that roughly half of a typical estimate is based on process steps which have labor standards developed from current production composite parts.

The following subsections describe each keel design and its corresponding manufacturing plans, controlling criteria, and cost/weight results.

Family C Designs

Design C1

Design Description. The Design C1 keel assembly is shown in Figure 4. The design incorporates discrete aluminum (7150) keel chords which are mechanically fastened to a skin/stringer panel. Load is introduced into each keel chord from the forward section via a combination of two titanium (6AL-4V) splice straps with Inconel bolts, and direct bearing via an aluminum compression plate which fills the gap between each pair of Section 45 and Section 46 keel beams. The curved skin is flattened where it attaches to the keel chords which are external to the skin OML. A layer of fiberglass protects against corrosion between the aluminum keel beams and the composite skin.

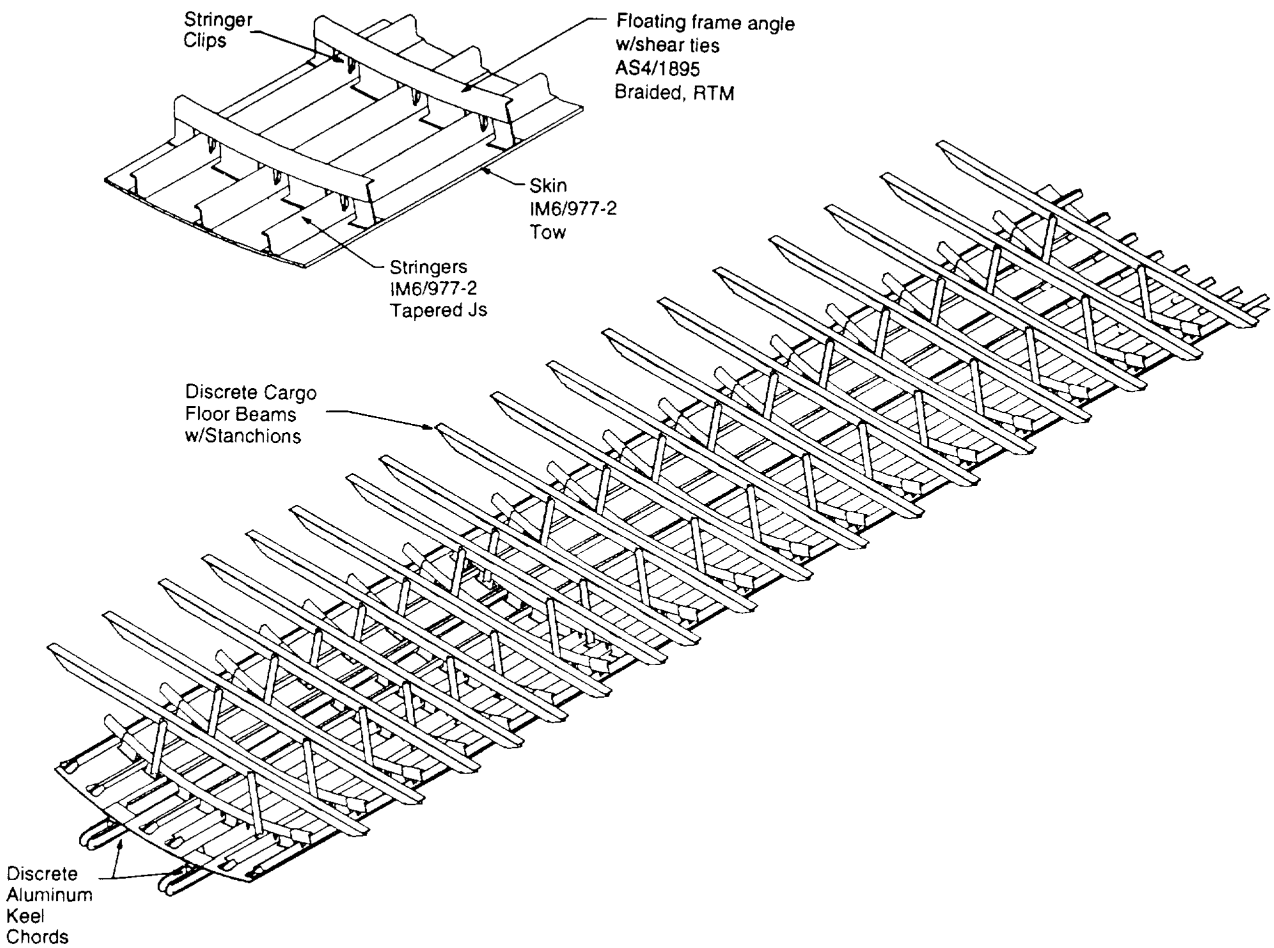

Figure 4: Design C1 Keel Assembly

The J stringers taper down in thickness proportional to the decreasing loads in the forward to aft direction. Where necessary, the width of the stringer base also varies to accommodate attachment to the keel chords. Stringers are spaced approximately 10-11" apart. The skin thickness is constant across the width of the panel in approximately the forward third of its length, then varies to match the asymmetrical loading (due to the cargo door cutout) in the remainder of the panel. The rate at which skin plies are dropped is limited by the ability of the precured stringers to conform to the profile of the cobonded skin. The design reflects a maximum drop rate of approximately 1 ply every 5 inches. Both skin and stringer use IM6/977-2 material.

The multi-piece frames include shear ties, an inner angle section, and stringer clips. The shear ties are blade sections which are cobonded to the skin in the areas between the stringers. The frame angle is mechanically fastened to the shear ties and to the webs of the J stringers via the stringer clips. The frame angles and shear ties use AS4/1895[7] type material; the clips use AS4/3501-6.

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[7] 1895 is a resin system produced by Shell Chemical Co.

The cargo support structure for Design C1 features a discrete J-section cargo floor beam and two T-section stanchions. Angles are provided at the roller tray locations to support the flanges of the floor beam. The beam and support angles use fabric, the stanchions use tape; all are pultruded with AS4/3501-6 equivalent material.

Manufacturing Plans. The baseline fabrication method originally chosen for the keel skins employed batch processing using the same equipment and the same 360° tooling as the crown (Reference 1). This approach was abandoned as a result of cost studies done on the actual keel designs. Although larger charge sizes usually result in higher material laydown rates, a point of diminishing returns is reached where gains in the production rate do not justify the increased tooling, handling, storage life, and storage costs. The fabrication method selected for the Design C1 keel skin is tow placement on a two-at-a-time clamshell winding mandrel followed by a transfer of the skin to an OML cure tool (Figure 5). An OML tool is employed due to the criticality of the attachment of the aluminum keel chords to the outside of the skin panel. Viton bagging provides the IML surface.

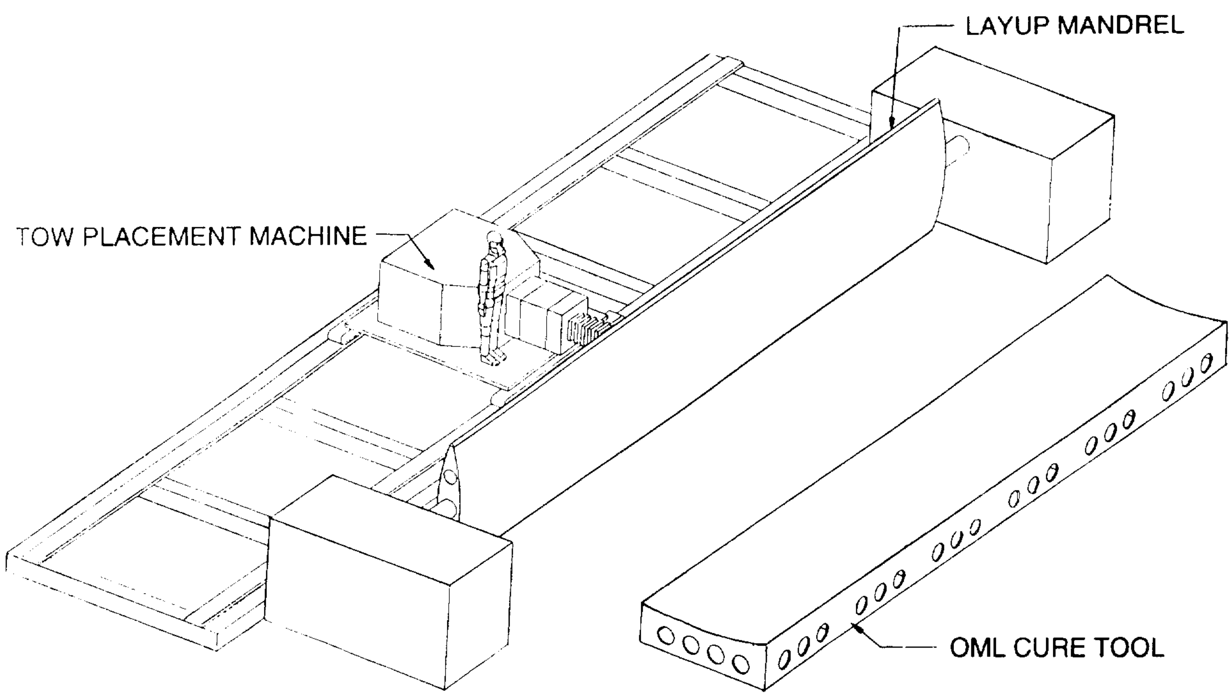

Figure 5: Tow Placement of C1 Keel Skin

Due to the large number of ply drops in the skin, the IML surface exhibits significant contour change. Use of a multi-piece frame minimizes the amount of RTM frame tooling required to match the contour. The shear ties and the frame angles to which they attach are cut from triaxially (2-D) braided/RTM J-sections. The stringer clips are pultruded. The tapered J stringers utilize automated layup and automated hot drape forming. Both the stringers and shear ties are precured and cobonded to the skin.

The keel chords are machined from aluminum extrusions. They are mechanically attached to the cured panel with a cocured fiberglass isolator at the interface. The compression plates carrying load into the keel chords are machined after casting a pattern in the void between the two assembled in-line keel chords of Sections 45 and 46. The longitudinal panel lap splice incorporates an automated layup and hot drape formed cured stringer along with automated fastening due to the clear access. The fuselage frame is then attached to the shear ties using thermoplastic rivets. Stringer clips and the braided/RTM frame splices are then fastened in place, followed by completion of the aft circumferential splice joint. The pultruded cargo floor beam and stanchions are then assembled to the keel panel. The installation is completed after the forward circumferential splice attachment is achieved.

Design Drivers. Figure 6 is a schematic showing where specific design issues tend to be critical in the Design C1 keel panel. The figure shows the important areas of load redistribution: the keel beam to skin joint, and the areas of high shear adjacent to the keel beam. Most of the stiffened skin panel is dominated by axial compression and the minimum stiffness requirements. Minimum skin buckling becomes a driver toward the aft end where skin gages are lighter, especially in the area of increased load near the cargo door opening. Although axial loads are lower in the far aft end, the corresponding reduction in skin gages is limited by hoop tension damage tolerance.

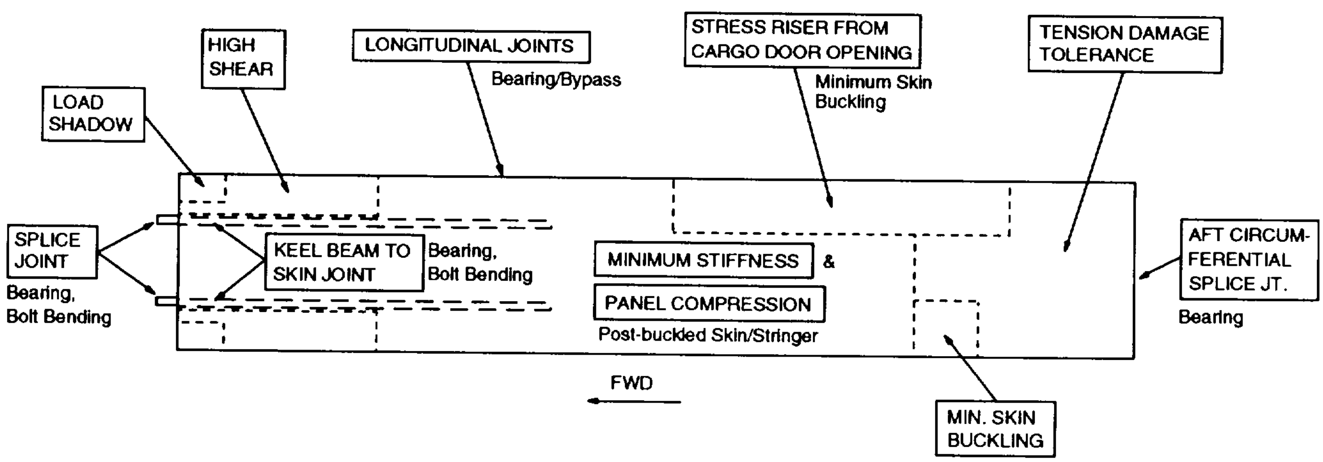

Figure 6: Critical Issues for Design C1 Keel Panel

Fastener bearing in the aft circumferential splice joint controls the skin thickness at that location, which is sized to allow the use of only two rows of fasteners per side. The longitudinal joints are controlled by bearing/bypass strength under combined hoop tension and shear loads.

At the forward splice of each keel chord the ULTIMATE compression condition relies on the bolts and splice plates to react all of the bending load but only the axial load up to LIMIT. The remaining axial load up to ULTIMATE is reacted in direct bearing by the compression plate. For the ULTIMATE tension and LIMIT compression loads the compression plate is assumed ineffective and all axial and bending loads are reacted through the bolts and splice plates. The titanium splice plates are sized not only to carry the loads but also to provide the desired bolt load distribution. High strength Inconel bolts are used for their capability to resist bolt bending.

Strain compatibility of the keel chords with the attached composite skin/stringer panel restrains the aluminum from being loaded to its full capability. The flanges of each T-section keel chord are bolted through both the skin and the bottom flanges of the J-stiffener above to provide the maximum bearing area in the composite material. For this reason the width of the keel beam web directly controls the required width of the adjacent J stiffener. The forward depth of the tapered keel chord, and therefore the rate of taper, is limited by its effect on panel bending loads due to eccentricities.

The thermal mismatch between the aluminum keel beam and the Gr/Ep stiffened skin was found not to be a critical issue for the C1 keel panel. The greatest thermally induced loads occur at about -40°F when the keel chords contract, thus adding to the compression loads in the attached skin. However, existing material test data indicate that the increase in compression damage tolerant allowable strains for the cold environment (with respect to hot/wet allowables) more than make up for the added thermal strains. The cold condition is therefore not a critical load case.

The frames were sized to provide the stiffness required to prevent general instability of the fuselage. Strength checks were also conducted and revealed the flight loads were not critical once the stiffness criteria were met. The minimum cross section of the multi-piece frame occurs over the stringer where the inner angle spans between shear ties. The frame must also react out-of-plane loads due to eccentricities in the longitudinal load path of the stiffened skin and distribute concentrated loads from the cargo support structure. The fasteners connecting the inner frame angle to the shear ties carry both these reaction loads and the shear flow acting along the length of the frame.

The cargo support structure for Design C1 uses a large cargo floor beam and a minimum number of stanchions (two) to beam out the loads acting at the locations of the eight roller trays. The floor beam is critical for bending strain due to flight loads. The upper flanges of the J-section floor beam are supported against bending by mechanically fastened clips at the roller tray locations.

Design C2

Design Description. The Design C2 keel assembly is shown in Figure 7. Design C2 is similar to Design C1 in that it incorporates a skin stiffened with cobonded, precured J stringers. Rather than discrete keel chords, however, Design C2 utilizes a thick laminate skin to carry the high compressive loads which exist at the forward end of the keel. The thick laminate acts as a panelized keel beam by spreading the equivalent material of the discrete keel chords across a wide section of the keel panel. This panelized keel beam tabs out from the forward end of Section 46 to accept load from the forward section via two bolted titanium (6AL-4V) splice plates. Both D Family designs have similar panelized keel beam and joint details.

The Design C2 J stringers maintain constant geometry the full length of the panel. Blade stringers, also of constant geometry, are used along the longitudinal splice joints; however, these are fastened in place rather than cobonded. As in Design C1, the stringers are spaced approximately 10-11" apart. The thick skin in the forward center of the panel tapers down to the sides and to the aft end where the loads are lighter. The asymmetrical skin thicknesses in approximately the aft two-thirds of the panel reflect the loads in that area. Because the Design C2 panel uses IML tooling, the precured stringers have a smooth surface to bond to and do not limit the rate of ply drops in the skin as they did in Design C1 which uses OML tooling. While the IML tooling pushes the skin thickness variations to the outside, the greatest ramp rates occur in the forward portion of the panel which is inside the fairing. Aerodynamic smoothness is therefore maintained. Both skin and stringers are AS4/3501-6 material.

The frames, which are cobonded to the skin, are one-piece triaxially (2-D) braided Js with mouse holes over the stringers. Clips fasten the stringer webs to the frames at the mouse hole locations. Frames are made of AS4/1895 type material and clips are AS4/3501-6.

The cargo support structure for Design C2 is similar to that for Design C1 in that it features discrete floor beams and stanchions; however, Design C2 uses a larger number of smaller sized elements. The six stanchions are C-channels, the cargo floor beam is a J-section. Angles are provided at the roller tray locations to support the flanges of the floor beam. The stanchions, beam, and support angles all use tape; all are pultruded with AS4/3501-6 equivalent material.

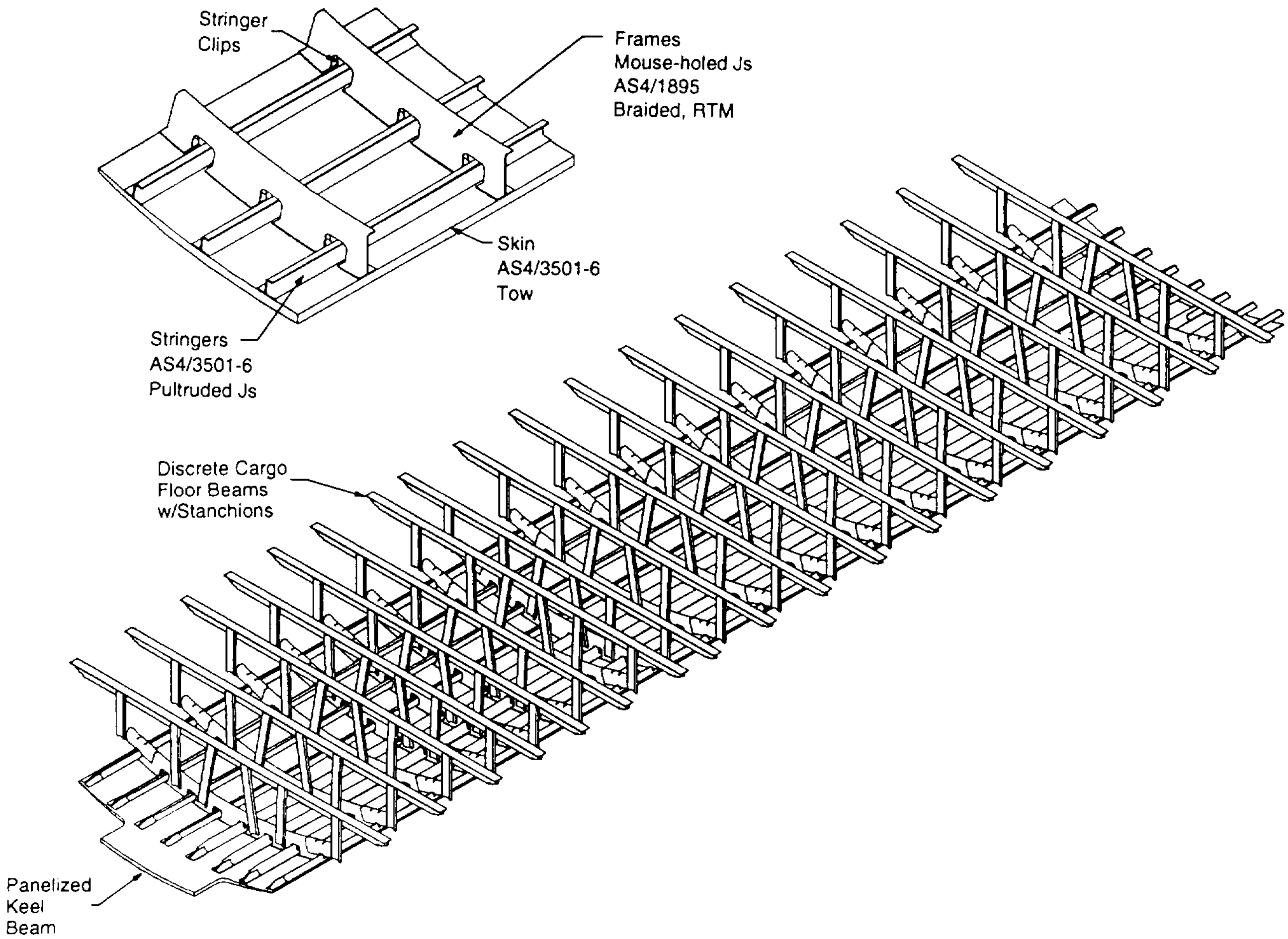

Figure 7: Design C2 Keel Assembly

Manufacturing Plans. The keel skin for Design C2 is tow placed directly over the cure tool, as illustrated in Figure 8. The use of IML tooling resulted in a constant IML surface allowing for the use of a one piece braided/RTM frame. The use of constant gage J stringers allows for the efficient use of pultrusion. The precured frames and stringers are located in the IML tool and the skin is tow placed over the details. The subsequent oven/vacuum bag operation cures the skin and cobonds it to the frames and stringers.

The stringers at the longitudinal lap splices are automated dry fabric layup pultrusions. As with Design C1, the clear access allows for automated fastening. The automated layup hot drape formed and cured frame splices are then installed, after which the aft circumferential splice is completed. The pultruded cargo floor beams and stanchions are then assembled to the keel panel. The installation is completed with the forward circumferential splice attachment.

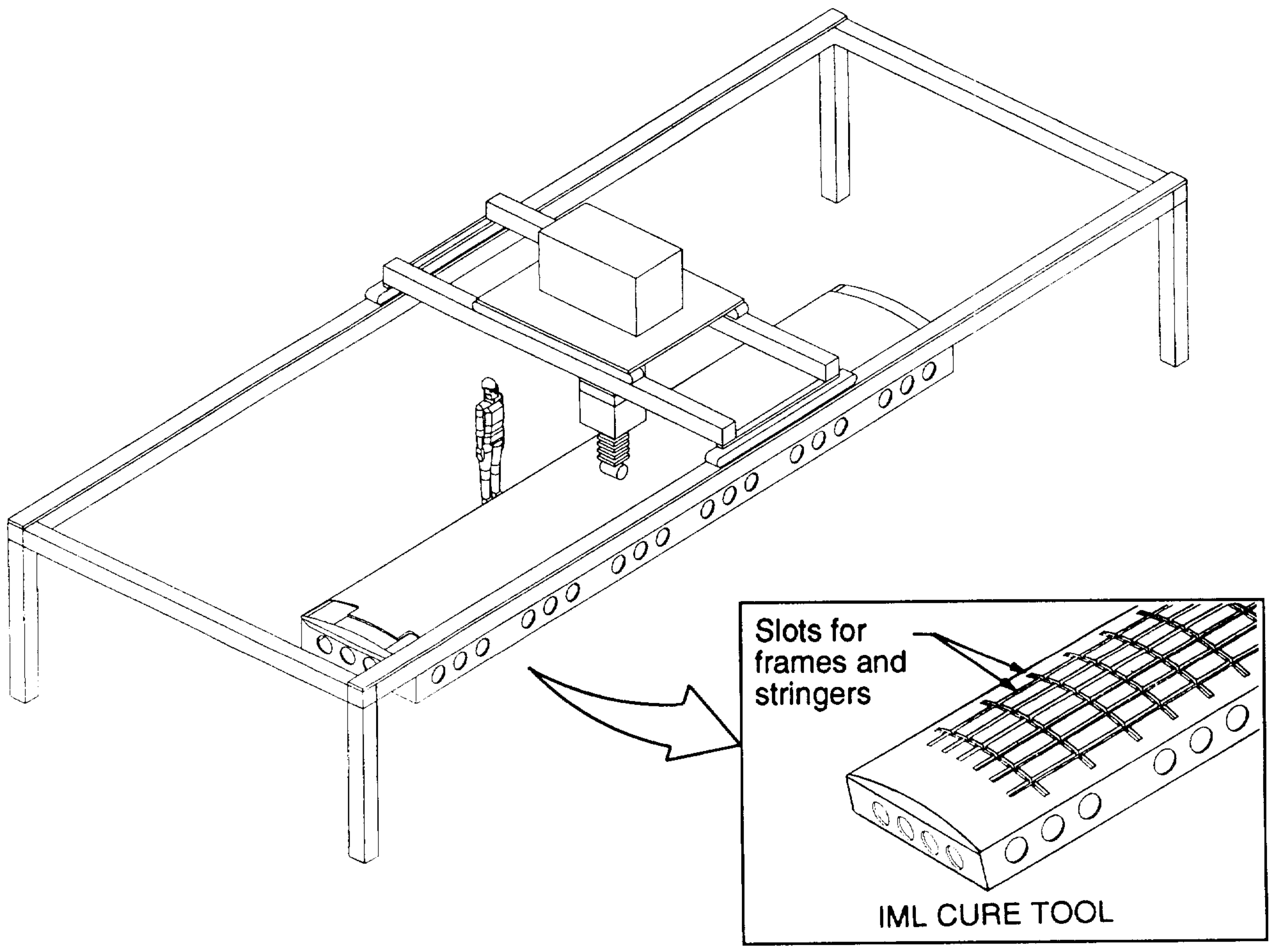

Figure 8: Tow Placement of Design C2 Panel

Design Drivers. Figure 9 shows in schematic form the areas where certain design issues are critical for the Design C2 keel panel. Many of the design drivers are similar to those shown for Design C1. The major area of difference is at the forward end where Design C2 has a very thick skin acting as a panelized keel beam in place of discrete keel cords. The thick skin easily satisfies the minimum shear stiffness requirement, which only becomes a design driver toward the aft end where the panelized keel beam has tapered out. As plies are dropped from the thick laminate, bending loads are introduced due to eccentricities in the load path, and add to the compression strains which dominate the forward two-thirds of the panel. As in Design C1, the skin in much of the aft end is controlled by minimum skin buckling. However, tension damage tolerance does not drive the skin gages in the aft end of Design C2 as it did Design C1. This is due to the better tension fracture performance under large crack sizes demonstrated by the AS4/3501-6 system as compared with AS4/977-2.

Like Design C1, the longitudinal joints are controlled by bearing/bypass strength, and the aft circumferential splice joint is critical for fastener bearing. The required skin thicknesses at the joints for Design C2 are sometimes greater due to the lesser bearing properties of the AS4/3501-6 material. The forward splice joint at the panel tab out is bearing and bypass critical. Note that this forward splice joint design, unlike Design C1, has no direct bearing capability and the full ULTIMATE compression load is carried through the bolts and splice plates. The titanium splice plates were sized to provide a fairly uniform bolt load distribution and to hold the joint to only three rows of fasteners per side.

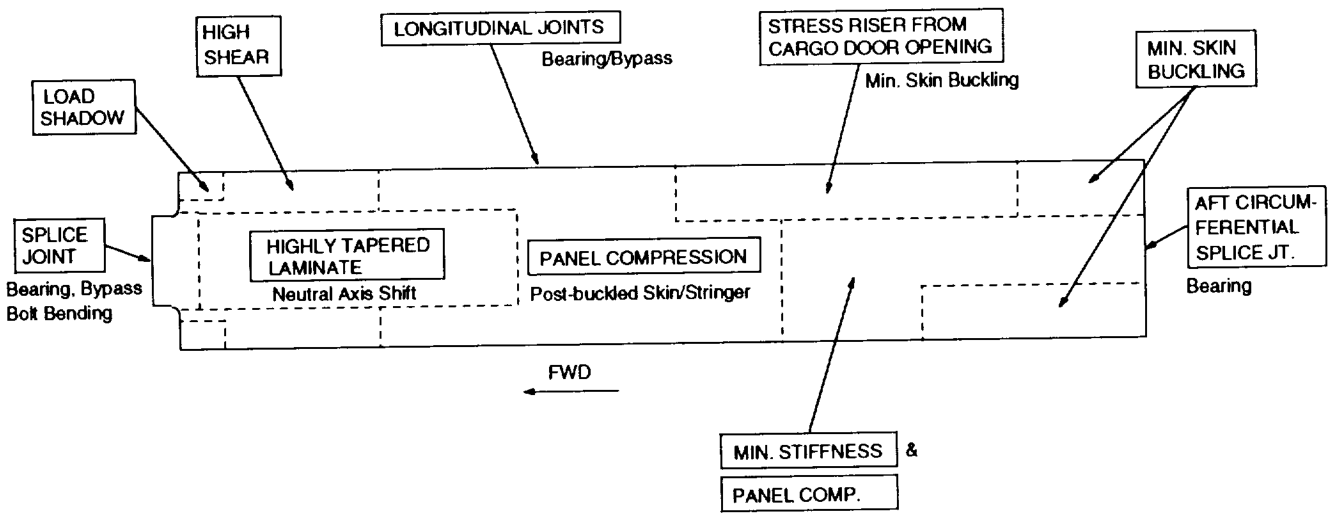

Figure 9: Critical Issues for Design C2 Keel Panel

The frames are stiffness designed to prevent general instability. The most strength critical area is where the mouse holes are cut from the frame cross section to accommodate the stringers. Pressure combined with flight loads results in the most severe combination of axial and bending loads, producing a maximum strain at the inner edge of the frame. The effect of stress concentrations at the mouse holes is not a design driver since the edge of the mouse hole cutout is in the middle of the bending section, away from the more highly stressed frame inner edge.

The cargo support structure for Design C2 utilizes a six stanchion configuration with supports directly beneath the roller trays. This greatly reduces the bending loads in the floor beam as compared with Design C1, and the floor beam of Design C2 is downsized accordingly. Design C2 also provides greater stiffness than Design C1 and, as a result, may improve the functioning of the cargo handling equipment. Like Design C1, Design C2 includes mechanically fastened clips at the roller tray locations to support the upper flanges of the J-section floor beams against bending.

Family C Cost Results

Cost results for the Family C keel designs are shown in Figure 10. The figure shows costs for the total keel assembly and for each of the six major processes which comprise it. These costs are further categorized into nonrecurring costs and recurring material and labor costs. All costs are expressed as a relative percentage of the total metal keel baseline cost.

The total cost for Design C1 is 103% and Design C2 is 82% of the total metal keel baseline cost. Note that this cost data is for the non-optimized composite designs, and is therefore intended primarily to identify the differences between variations within the design family. Cost comparisons between the metal and the globally optimized composite designs are given later.

The panel fabrication and assembly (including keel chords) is 34% of the total metal keel panel cost for Design C1 and 26% for Design C2. The labor cost is affected in two main areas. The first is the skin fabrication in which Design C1 utilizes a winding mandrel and subsequent transfer to the cure tool, while Design C2 calls for material placement directly on the cure tool. The winding mandrel approach of Design C1 provides a slightly improved layup rate as compared with Design C2, but not enough to justify the increased tooling and handling costs. The second area affecting labor costs is the tooling approach. The IML tool of Design C2 simplifies the procedure for bagging and locating stiffening elements. This results in significant labor cost savings over the

OML tooling approach of Design C1, although the savings are offset somewhat by the higher cost of the more complex IML tool.

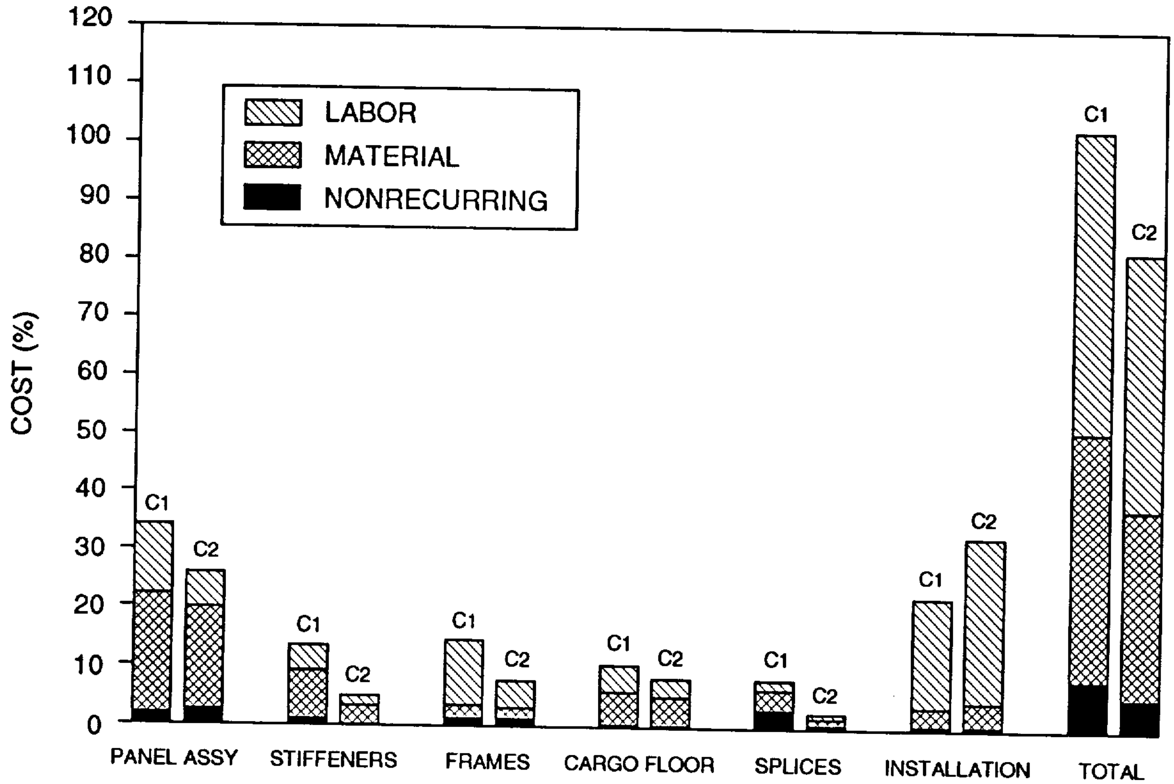

Figure 10: Family C Cost Results

The panel material costs are also affected in two main areas. The first difference results from the IM6 fiber used in Design C1 which is 32% more expensive than the AS4 fiber used in Design C2. The second difference arises from the material used in the keel beam designs: aluminum for the discrete keel chords of Design C1, AS4/3501-6 for the panelized keel beam of Design C2. The raw material cost per pound for the aluminum is only 62% of the AS4/3501-6 material; however, after machining and assembly are taken into account, the cost per pound of the aluminum keel chords jumps to 131% of the composite panelized keel beam.

Stiffener fabrication was 13% (Design C1) and 5% (Design C2) of the total metal keel panel cost. Significant labor savings result for the Design C2 stringers which are constant section and can therefore be pultruded. The stringers for Design C1 are required to be tapered and utilize automated layup and manual hot drape forming. While automating the hot drape forming process would help improve the efficiency of the Design C1 stringer fabrication, the large batch sizes inherent in pultrusion would be hard to better. The differences in material costs between the two designs was due to the use of the more expensive IM6 fiber for Design C1 along with a design that requires a large amount of material wastage. The stringers for Design C2 utilized the less expensive AS4 fiber along with automatically stacked and lightly stitched dry tape preform.

Frame fabrication amounted to 15% of the total metal keel panel cost for Design C1 and 8% for Design C2. The labor cost doubled for the multi-piece frame used in Design C1, due largely to the assembly, as compared with the one piece frame used in Design C2.

Cargo floorbeam fabrication was 11% (Design C1) and 8% (Design C2) of the total metal keel panel cost. The use of prestacked dry tape preforms for both stanchion and floorbeam pultrusions of Design C2 versus the automated dry fabric layup and kitting in Design C1 is responsible for most of the difference in labor costs.

The splice fabrication was 8% (Design C1) and 3% (Design C2) of the total metal keel panel cost. The primary reason for the difference between the two Family C designs is the design of untapered parts allowing the consistent use of pultrusion in Design C2.

The keel panel installation was 22% (Design C1) and 33% (Design C2) of the total metal keel panel cost. The first major difference between the two is the design of the cargo support structure: a two stanchion configuration for Design C1, six stanchions for Design C2. This has a significant effect on cost (7% for Design C1 versus 17% for Design C2), while providing only a minimal improvement in weight for Design C2. The second major difference is the forward splice design. Design C1 splices its discrete keel chords in a manner similar to the current metal technology. Design C2 utilizes a double shear tab out splice. While the two approaches are very different, the resultant costs are about the same.

Family C Weight Results

The weight results for the non-optimized Family C keel designs are shown in Figure 11. Weights are given for the total keel assembly and for each of the same six major processes used in the cost comparisons. All weights are expressed relative to the total metal keel baseline weight. Design C1 shows a total weight 87% of the metal baseline; Design C2 is 88%. Only minor differences between the weights of the various designs were found.

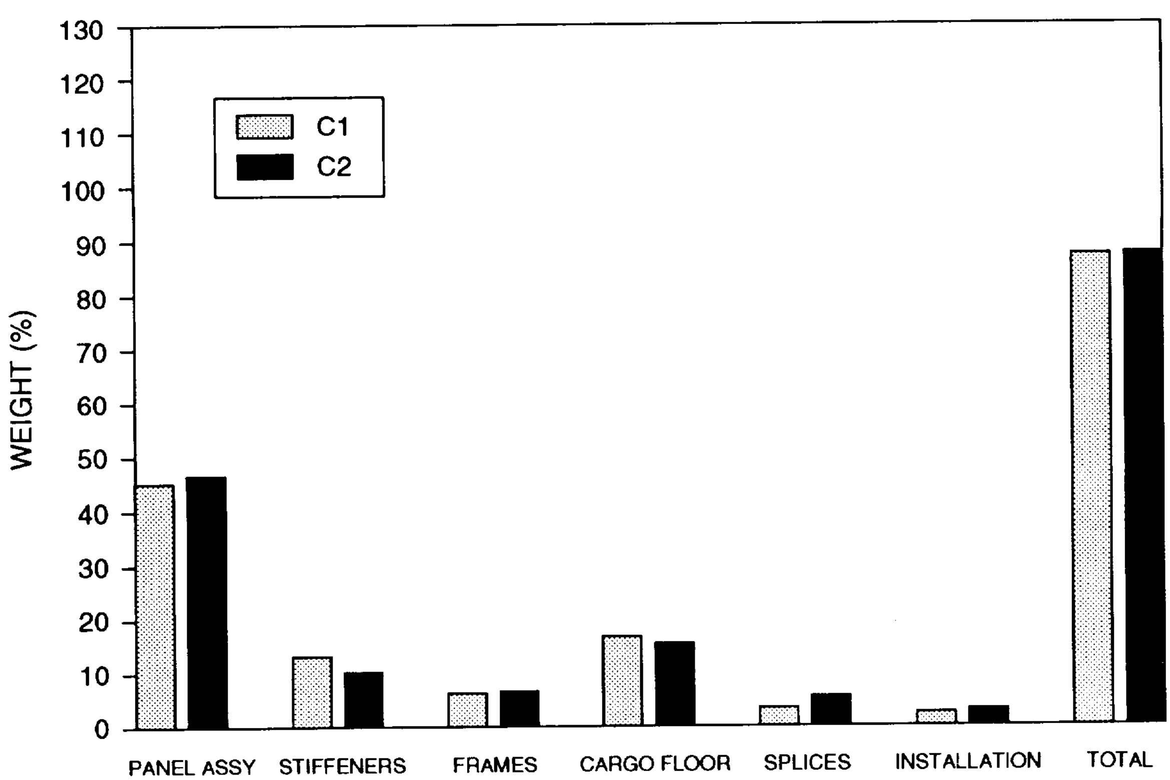

Figure 11: Family C Weight Results

Family D Designs

Design D1

Design Description. The Design D1 keel assembly is shown in Figure 12. The design utilizes a thick laminate to carry the high compressive loads which exist at the forward end of the keel, and transitions to sandwich construction as the loads reduce further aft. The thick laminate acts as a panelized keel beam by spreading the equivalent material of the discrete keel chords across a wide section of the keel panel. The panelized keel beam tabs out from the forward end of Section 46 to accept load from the forward section via two bolted titanium (6AL-4V) splice plates. Moving to the rear of the panel, the thick laminate is tapered out, and the change in thickness is made up by an insert of core material which allows the inner radius of the panel to remain constant along its length. The constant inner radius reduces the number of individual frames which would otherwise need to be manufactured. The sandwich construction eliminates the need for stringers. The panel incorporates panned-down edges to provide a solid laminate for splicing to adjacent structures. A blade stiffener is fastened to the skin along each panned-down longitudinal splice edge to provide stability.

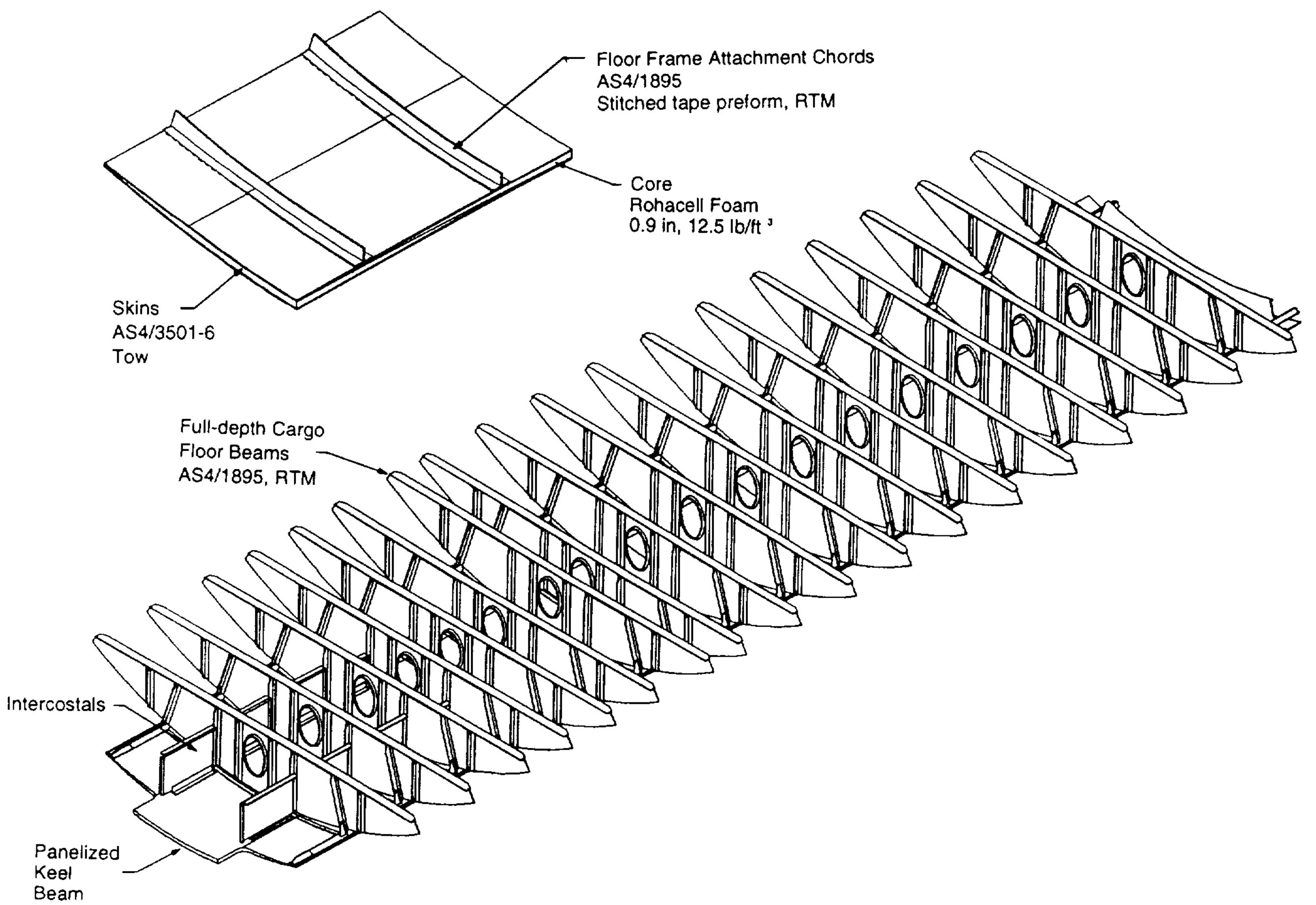

Figure 12: Design D1 Keel Assembly

The frames in the D1 keel section are integral with the cargo support structure to form a full-depth beam. This is accomplished by cobonding blades onto the skin and then mechanically fastening these to the stiffened web which comprises the rest of the frame/cargo beam. At the forward end of the keel panel, intercostals are used to stabilize the thick "skin" against buckling. These are also accomplished by fastening to blades which have been cobonded to the skin.

Design D1 utilizes a 12.5 lb/ft^3 foam core material, and the sandwich skins are high resin content (42%) tow placed AS4/3501-6. The full-depth cargo floor beam is fabric material equivalent to AS4/1895. The longitudinal edge stiffeners are AS4/3501-6 type material in stitched tape form. Design variations D1A and D1B were developed to evaluate different materials and processes for the intercostals, intercostal attachment blades, and frame blades. All intercostal blades and frame blades use AS4 type fiber; however, Design D1A uses fabric prepreg and 3501-6 type resin, while D1B uses stitched tape preform and 1895 type resin. Intercostals are AS4/1895 type stitched tape for D1A and AS4/ACP-2(PEEK)[8] thermoplastic for D1B.

Manufacturing Plans. Design D1 uses IML tooling in order to standardize all the frame and intercostal attachment chords which are precured, fitted into slots in the tool, and cobonded to the panel. Two manufacturing methods are identified for the attachment chords. The first method (D1A) employs hand layup prepreg fabric which is hot draped formed, assembled, and cured. The second method (D1B) utilizes prestacked tape and resin transfer molding.

The skins are fabricated in a manner similar to Design C1; however, due to the use of IML tooling, a concave winding tool is required (Figure 13). After the precured attachment chords are in place, the tow placed skin is transferred to the cure tool. Vacuum pressure is used to hold the skin panel to the winding tool until it can be located directly over the cure tool.

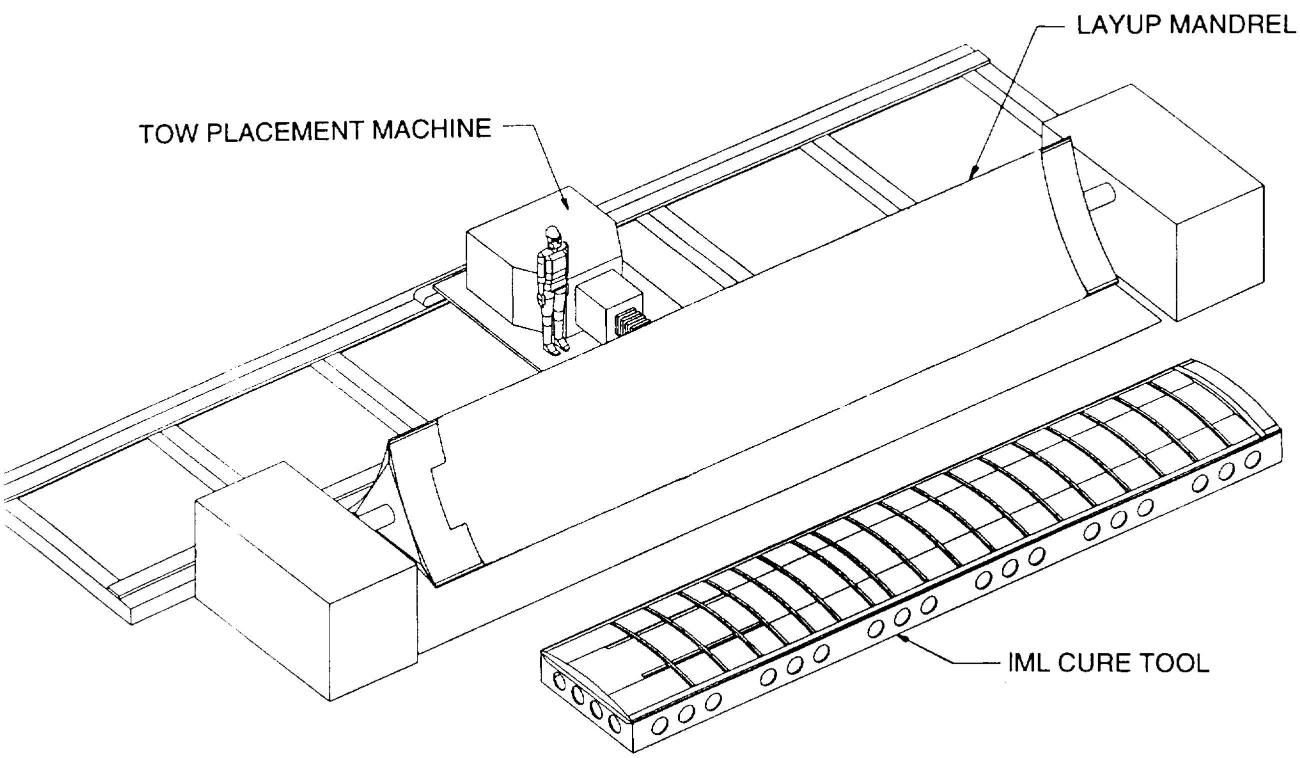

Figure 13: Tow Placement of Design D1 Keel Skin

[8] ACP-2 is a resin system produced by ICI/Fiberite, Inc.

The fabrication of the Rohacell core with its double taper and curvature represents a significant challenge in fabrication, handling and locating. The OML surface of the core is cut prior to the forming of the curvature. Then, after an oven/vacuum bag operation has induced curvature into the core while it is in the forming tool, barrel cutters are used to trim the IML surface. The foam core is then located onto the cure tool, with the inner skin and precured attachment chords already in place, and the outer skin is placed over the core. The assembly is then oven/vacuum bag cured.

Design D1 includes a full depth resin transfer molded cargo floor beam. Individual dry preform stiffening elements are located into the cure tool, followed by the web charge. The dry preform is then resin infused, cured and trimmed. Intercostals are resin transfer molded for D1A and pressformed thermoplastic for D1B.

Once the sandwich panel with cobonded attachment chords is completed, the longitudinal lap splice is accomplished using a stitched tape pultruded stringer along with automated fastening due to the clear access. The aft circumferential splice joint is then completed. This step is followed by the installation of the full depth cargo floor beams which are fastened to the co-bonded chords. The stitched tape/RTM or thermoplastic intercostals are then installed in the first four bays at the forward end. Then the pultruded frame splices are mechanically fastened. Lastly, the forward splice installation is completed using two titanium splice plates.

Design Drivers. Figure 14 is a schematic showing where specific design issues tend to be critical in the Family D Designs for the keel panel. The forward end is driven by the areas of high shear and panel compression, much like Design C2 which also has a panelized keel beam. Without stiffeners however, Design D1 requires intercostals in the first four bays to provide panel stability. The absence of stiffeners also requires the sandwich skins to remain fairly thick toward the aft end of the keel. As a result, neither the minimum shear stiffness or the tension damage tolerance requirements become critical. As the thick laminate transitions to a sandwich structure, the rate of ply drops in the longitudinal direction is limited by the resulting shifts in the neutral axis, which add bending loads. Along the panned-down longitudinal edges, blade stiffeners are attached to compensate for the loss of bending stiffness (and therefore column stability) provided by the sandwich construction.

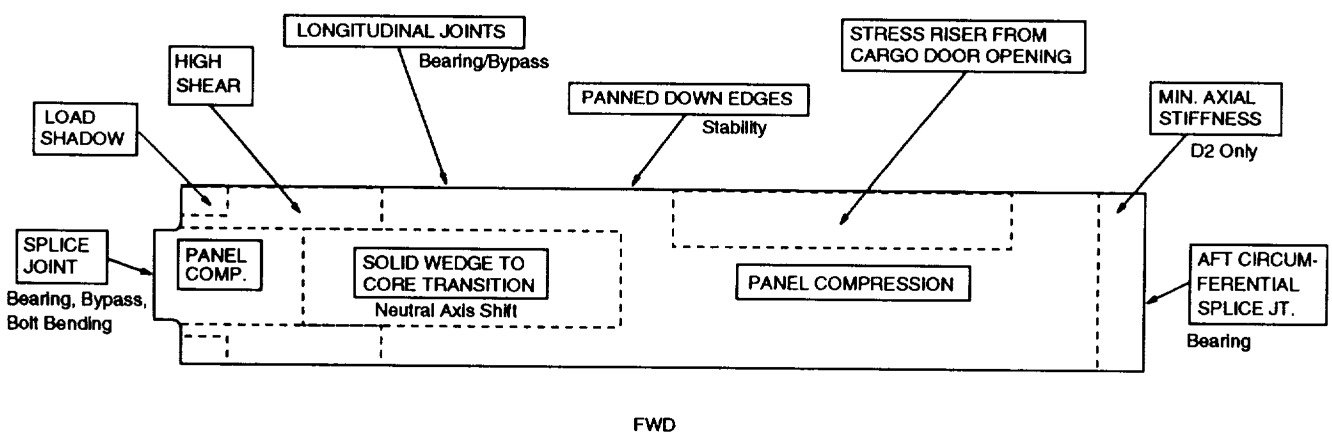

Figure 14: Critical Issues for Design Family D Keel Panels

The intercostals are designed to provide a reaction equal to 7% of the compressive load in the panel they are stabilizing. The most forward intercostal is therefore the most highly loaded, and is sized accordingly. The differences between the D1A and D1B intercostals reflect the properties of the different materials. The addition of a vertical stiffener to break up the buckle pattern and allow a thinner gage was considered but dismissed as too expensive for the amount of weight saved, especially since a minimum intercostal thickness is nevertheless required at the attachment to the skin-bonded blade where fastener bearing is critical.

The panned-down edges of the sandwich panel provide joint details much like the Family C Designs. The longitudinal joints are controlled by bearing/bypass strength, and the aft circumferential splice joint is critical for fastener bearing. The forward splice joint at the panel tab out is very similar to that of Design C2.

The full-depth cargo floor beam acts as a stiffened post-buckled shear beam. Per the established criteria, the web of the beam was not allowed to buckle below 40% ULTIMATE load. The lower chord of the beam is formed by the blade-section frame which is cobonded to the skin panel. The upper chord is reinforced against flange bending as required beneath the roller trays by an integral angle and/or the ends of the vertical web stiffeners. The access hole cut from the center of the beam is reinforced around its edges with an upstanding flange.

Design D2

Design Description. The Design D2 keel assembly is shown in Figure 15. The D2 design is very similar to D1, with a panelized keel beam transitioning to a sandwich structure. The major differences between the two D designs are the materials and the configuration of the frames and cargo support structure. The D2 skins use toughened resin 977-2 with AS4 fibers. The sandwich core is a 6.0 lb/ft^3 graphite/thermoplastic honeycomb. An edge filler of 12.5 lb/ft^3 Rohacell foam is provided where machining the honeycomb to a knife edge would prove too difficult.

Design D2 has discrete cargo floor beams supported by two stanchions, all using AS4/3501-6 type material. The beams are pultruded Js made from fabric, with an integral radius filler running full length to support flange bending. The stanchions are pultruded Ts made from stitched tape. The stanchions fasten into the frames, which are Js fashioned from triaxially (2-D) braided material, equivalent to AS4/1895. The frames are cobonded to the skin. The D2 intercostals are very similar to those for D1 except the material is AS4/3501-6 prepreg fabric.

Manufacturing Plans. The method of fabrication for Design D2 utilizes an IML tool similar to that of Design D1. The IML tool provides standardization of all of the pultruded intercostal attachment chords and braided/RTM frames which are cobonded to the skin panel. As in Design D1, the IML tool is notched to accept the precured attachment chords and frames. Unlike Design D1, however, the skins for Design D2 are tow placed directly onto the cure tool. The thermoplastic honeycomb core is trimmed net and then formed into its curved shape. The core is transferred to the cure tool, with the inner skin, frames, and attachment chords already in place, and then the outer skin is tow placed over the core. The subsequent oven/vacuum bag operation yields a cured skin panel with cobonded attachment chords and frames.

The longitudinal lap splice is achieved using an automated layup dry fabric/pultruded stringer along with automated fastening due to the clear access. The frame splices are completed, followed by the aft circumferential splice joint. Then the pultruded floor beams and stanchions are fastened to the keel panel frames. The pressclave thermoset intercostals are then installed in the forward first four bays. The forward splice installation is then completed using two titanium splice plates.

Design Drivers. The drivers for the Design D2 keel panel are very similar to those for Design D1, and Figure 14 is again applicable in identifying the areas of critical design issues. The forward end is sized very closely to Design D1 because the splice joint at the tab out is the controlling factor. Further aft however, the toughened material used in Design D2 allows thinner skin gages and higher ramp rates for ply drop-offs. At the very aft end, the reduction of skin thickness is limited by the minimum axial stiffness requirement.

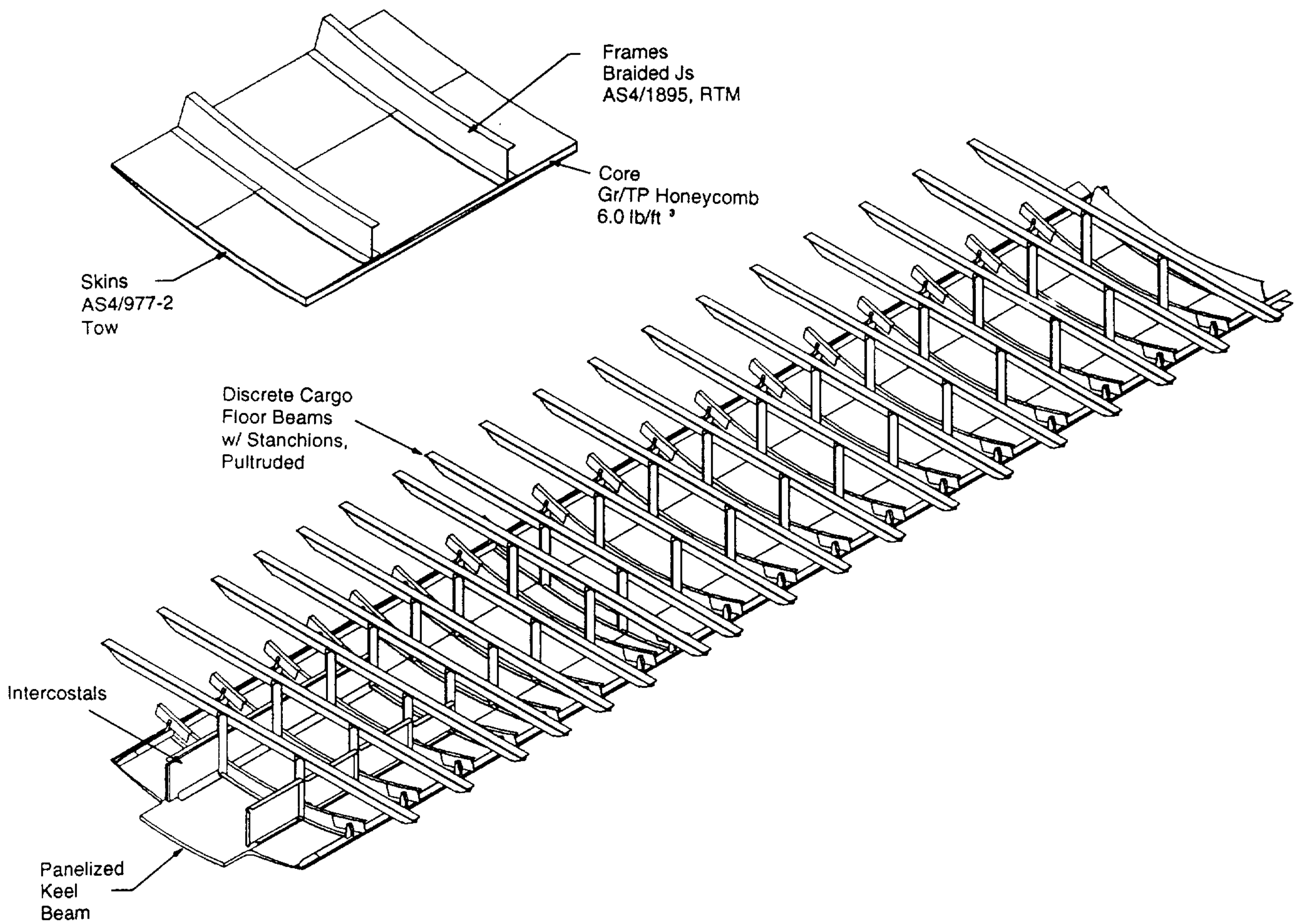

Figure 15: Design D2 Keel Assembly

The cargo support configuration for Design D2 is similar to Design C1, except the angles supporting the top flanges of the J-section floor beam are integral and run the full length of the beam. The two stanchions of Design D2 stand vertically, rather than slightly angled as in Design C1. The frames were sized in a manner similar to those of Design C2, without the complication of mouse holes.

Family D Cost Results

Cost results for the Family D keel designs are shown in Figure 16. The costs are expressed as a percentage of the metal keel baseline cost. The figure gives the total cost for the keel assembly and also a breakdown into six major processes. These costs are further broken down into nonrecurring costs and recurring material and labor costs.

The total cost was 117% (Design D1) and 119% (Design D2) of the metal baseline. Again, note that this cost data is for the non-optimized Family D composite designs, and is intended primarily to identify the differences between variations within the design family. Cost comparisons between the metal and the globally optimized composite designs are given later.

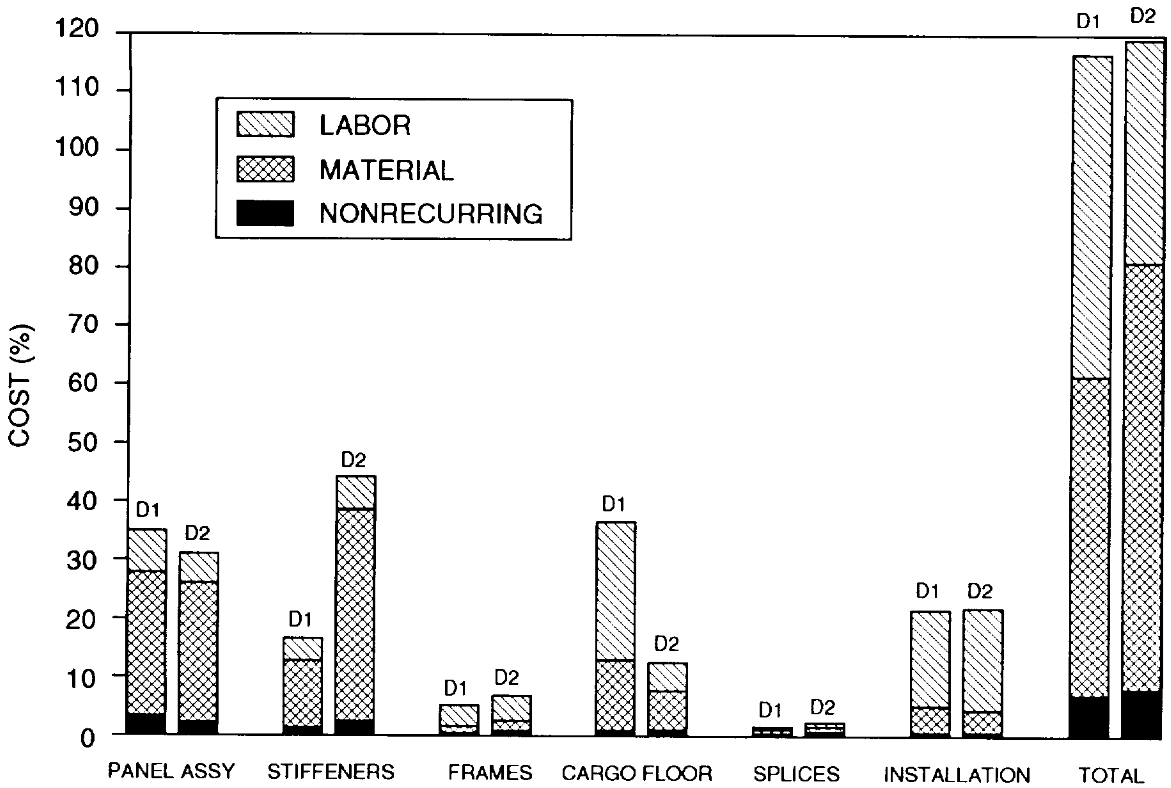

Figure 16: Family D Cost Results

The keel panel fabrication and assembly was 35% of the total metal keel panel cost for Design D1 and 31% for Design D2. As was the case with Family C, an improved material laydown rate in the winding method of Design D1 skin fabrication does not justify the additional tooling cost and labor steps associated with the process. Although only a six inch bandwidth was used for Design D1, increasing it to match the twelve inch bandwidth of Design D2 still wouldn't significantly reduce the overall cost. Automated fiber placement directly on the cure tool, as utilized in Design D2, offers a cost advantage.

Fabrication of the core and stiffening elements is 17% (Design D1) and 44% (Design D2) of the total metal keel panel cost. The major cost center of this process was the material cost associated with the core. While the thermoplastic honeycomb core used in Design D2 was half the weight of the Rohacell core used in Design D1, the associated material cost was 36% of the aluminum baseline versus only 11% for the Rohacell core. Most of the difference in labor costs between the two designs was due to the fabrication and assembly of the edge bands required for Design D2.

The frame fabrication was 5% (Design D1) and 7% (Design D2) of the total metal keel panel cost. While the two designs employed different fabrication methods, the cost difference was largely insignificant. However, direct comparisons are difficult due to the fundamental difference in the designs and the way in which the frames integrate with the cargo floor structure.

The cargo floor frame fabrication was 37% (Design D1) and 13% (Design D2) of the total metal keel panel cost. The difference in labor was due largely to the preforming of web stiffener charges and manual assembly of the full depth cargo floor beam of Design D1. Design D2, which utilizes pultrusion for its cargo floor beams and stanchions, takes advantage of the efficiency of large batch sizes and little touch labor. The material costs were also higher for Design D1 due to the higher weight, material cost, and wastage inherent in the full depth design.

Splice fabrication is 1.6% (Design D1) and 2.3% (Design D2) of the total metal keel panel cost. There were only slight differences between the two splice designs and processes.

Keel panel installation is approximately 22% of the total metal keel panel cost for both Design D1 and D2. The major difference in assembly was the installation of the cargo floor structure. While very different in procedure, the Design D1 full depth design cost 7.6% while the two stanchion configuration of Design D2 cost 6.6%.

Family D Weight Results

The weight results for the non-optimized Family D keel designs are shown in Figure 17. Weights are given for the total keel assembly and for each of the same six major sub-assemblies used in the cost comparisons. The weights given are relative to the total metal keel baseline weight.

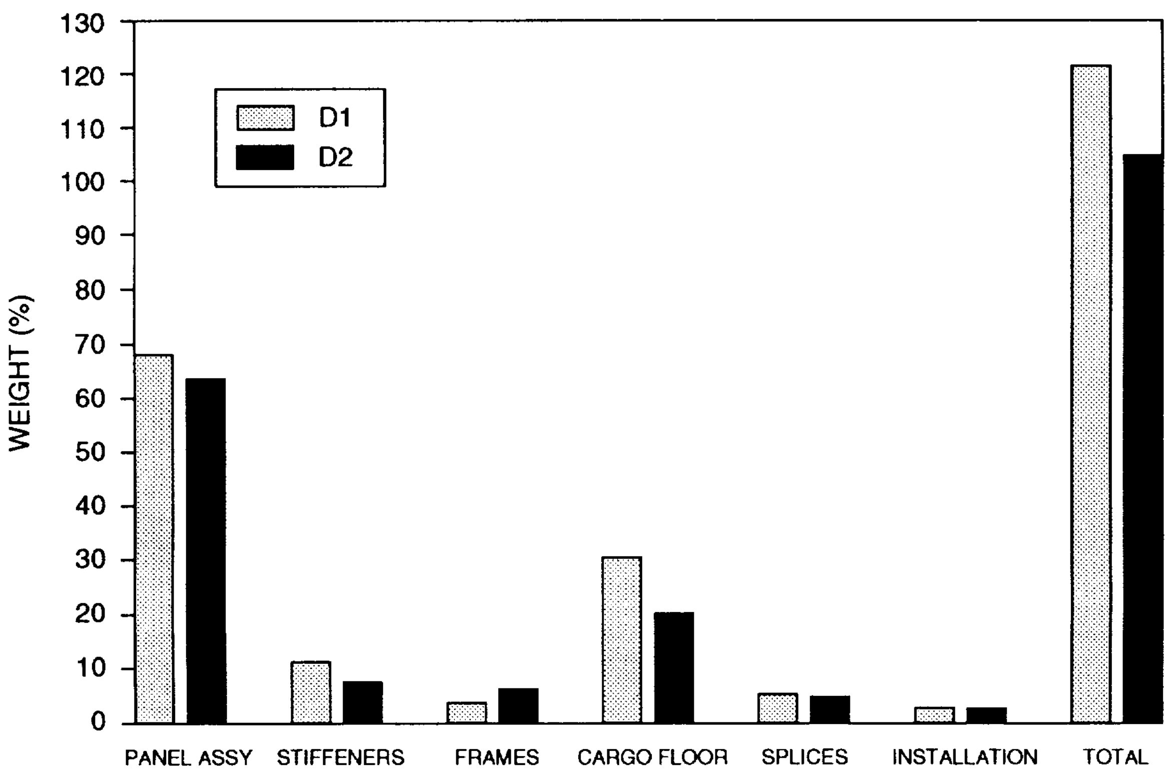

Figure 17: Family D Weight Results

The total weight is 121% (Design D1) and 105% (Design D2) of the baseline metal weight. The major cause of the weight difference is the dissimilarity between cargo floor structure designs: The full depth cargo floor beam of Design D1 is 30% of the total metal baseline weight, while the discrete floor beam/two stanchion configuration of Design D2 is only 20%. Other factors benefiting the Design D2 weight are thinner skin panel gages, which result from the use of toughened material, and the lighter thermoplastic core.

GLOBAL OPTIMIZATION

The previous section described four design concepts for a keel panel, two from Family C (bonded skin/stringer) and two from Family D (sandwich), and presented an evaluation of the cost and weight estimates for each. To more fully understand the potential of each family, "new" designs, beyond those studied in detail, were created by modifying and/or combining attractive elements of the original four concepts. The costs and weights of these new designs were estimated using engineering judgement based on the detailed values obtained for the original designs. This process is referred to as "mix-and-match." The goal of the mix-and-match effort was to arrive at an "optimum" design within each family.

In addition to the mix-and-match activity, steps were taken to eliminate inconsistencies in the criteria and analysis assumptions governing the designs of the two families. For instance, the difference in laminate orthotropy between the Family C and Family D designs penalized the weight of the Family D design. A harder, thinner laminate was applied instead to Designs D1 and D2 to account for this disparity. These extra designs are designated D1c and D2a. Also, the analyses were updated to incorporate more recent insight into the tension damage tolerance of specific material systems, cargo floor frame stiffness requirements, effective widths, and core density requirements. Other modifications to the original designs addressed the effects of tough resin (as opposed to brittle), a six stanchion cargo floor beam (as opposed to two), and stringer fabrication methods on the cost and weight of the keel design. A summary of both the original and modified designs is presented in Table 1, along with each design's total cost and weight relative to the baseline metal configuration.

Table 1: Results of the Global Evaluation Mix and Match Exercise

Design	Comments on Design	Skin Material	Core/Stringer Material	Cargo Frame Description	Relative Cost	Relative Weight
D1a	Original global evaluation design (Sandwich concept)	AS4/3501-6 42% R.C.	Rohacell (12 pcf)	Full depth design Hand L/U (fabric)	1.18	1.22
D1b	Original global evaluation design (Sandwich concept)	AS4/3501-6 42% R.C.	Rohacell (12 pcf)	Full depth design Stitch tape RTM	1.17	1.21
D1c	D1b with harder, thinner skins (Sandwich concept)	same as D1b	same as D1b	same as D1b	1.10	1.06
D1d	D1c with process change (Tow place on cure tool per D2b)	same as D1b	same as D1b	same as D1b	1.07	1.06
D2	Original global evaluation design (Sandwich concept)	AS4/977 42% R.C.	Hexcell HFT-G (6 pcf)	2 stanchion design Pultruded	1.19	1.05
D2a	D2 with harder, thinner skins (Sandwich concept)	same as D2	same as D2	same as D2	1.12	0.90
D2b	D2a with adjustment for layup rate to be consistent with other assumptions	same as D2	same as D2	same as D2	1.13	0.90
Dw	Combination of D2b material and layup, D1a core, 2 stanchion frame from C1	AS4/977 42% R.C.	Rohacell (12 pcf)	2 stanchion design from Design C1	0.83	0.90
Dx	Dw with D1d material and layup	AS4/3501-6 42% R.C.	same as Dw	same as Dw	0.83	0.95
Dy	Dw with a 6 stanchion frame design from design C2	AS4/977 42% R.C.	Rohacell (12 pcf)	6 stanchion design from Design C2	0.91	0.89
Dy'	**Dy with lighter core aft, corrected floor beam & stanchion stiffness, reduced fwd splice**	**AS4/977 42% R.C.**	**Rohacell (12 pcf fwd, 9 pcf aft)**	**6 stanchion design from Design C2**	**0.90**	**0.83**
Dz	Dy with an estimate for the effects of an in situ foam core. (Included for comparison only)	same as Dy	In situ foam core	same as Dy	0.86	0.92
C1	Original global evaluation design (Bonded skin/stringer)	IM6/977 42% R.C.	CTLM hot drape "J" (Alum chord)	2 stanchion design Pultruded	1.03	0.87
C1a	C1 with corrections to account for analysis errors and lower margins of safety	same as C1	same as C1	same as C1	1.02	0.86
C1b	C1a with an AS4/3501-6 material system	AS4/3501-6 42% R.C.	same as C1, but AS4/3501-6	same as C1	0.94	0.91
C1c	C1a with an AS4/977 material system	AS4/977 42% R.C.	same as C1, but AS4/977	same as C1	0.95	0.87
C2	Original global evaluation design (bonded skin/stringer)	AS4/3501-6 42% R.C.	Pultruded "J" panelized chord	6 stanchion design	0.82	0.88
C2a	C2 with corrections for analysis errors and lower margins of safety	same as C2	same as C2	same as C2	0.83	0.89
C2b	C2a with an AS4/977 material system	AS4/977 42% R.C.	same as C2, but AS4/977	same as C2	0.82	0.84
C2c	C2b with drape formed stringer fabrication from family C1 used	same as C2b	same as C1c	same as C2	0.85	0.84
C2c'	**C2c with corrected floor beam and stanchion stiffness, reduced fwd splice**	**AS4/977 42% R.C.**	**pnlzd, hot drape Js, AS4/977**	**6 stanchion design same as C2**	**0.85**	**0.80**

The best combinations for each design family are designated C2c' and Dy'; these are highlighted in Table 1. Both include the use of AS4/977-2 (toughened resin system) and a six stanchion design for the cargo floor beam. It should be noted that the two stanchion design used in these studies was less expensive to produce and slightly heavier than the six stanchion design, but after further consideration, only the six stanchion design was felt to satisfy the design requirements due to an imposed stiffness criteria. Also note that cost and/or weight could potentially be saved by using a sandwich design with in situ foam (Dz) or a stiffened skin with bonded, pultruded Js (C2b); however, the process and performance development required to achieve these designs presents too great a program risk within the scope of global evaluation. Such options may be revisited in the local optimization phase.

The costs and weights for the globally optimized keel designs are shown in Figures 18 and 19, respectively. The total cost of the optimized Family C design (C2c') was 85% of the metal baseline; the total cost of the optimized Family D design (Dy') was 90%. Weight comparisons reveal the C2c' design to weigh 80% of the metal baseline, while Dy' is 83% of the metal keel weight.

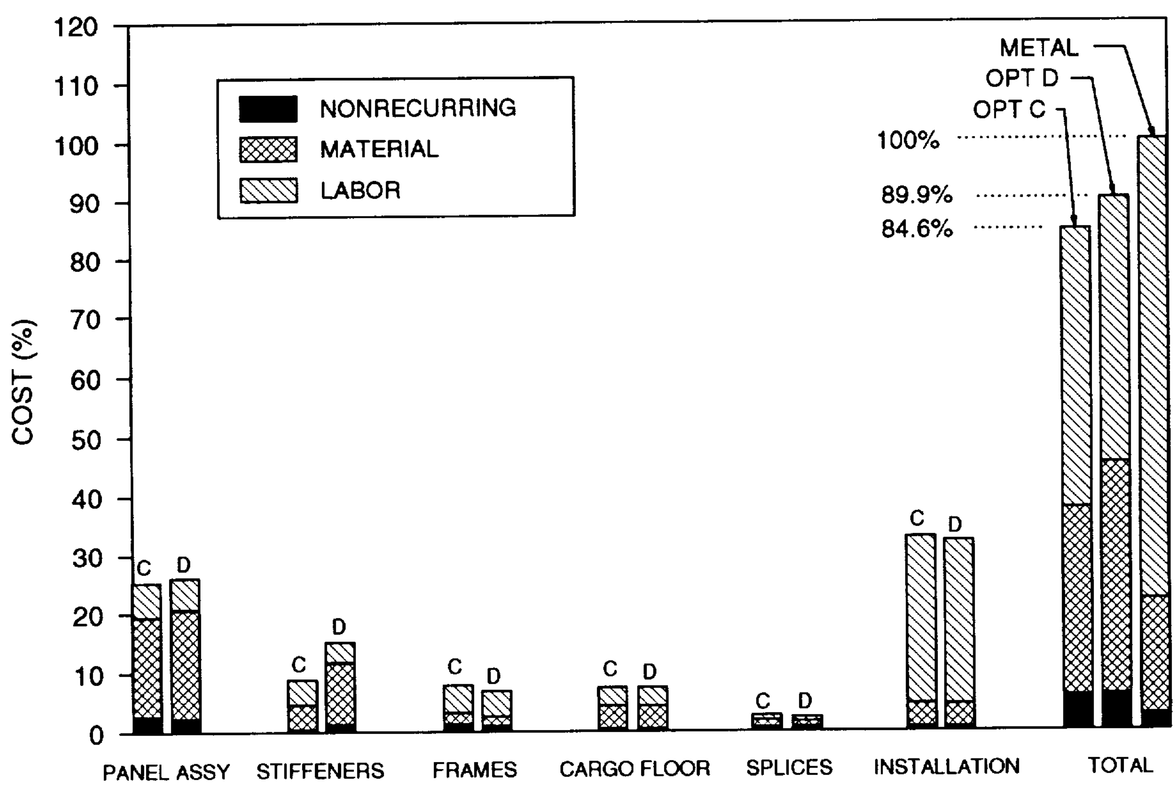

Figure 18: Cost Results for Globally Optimized Keel Designs

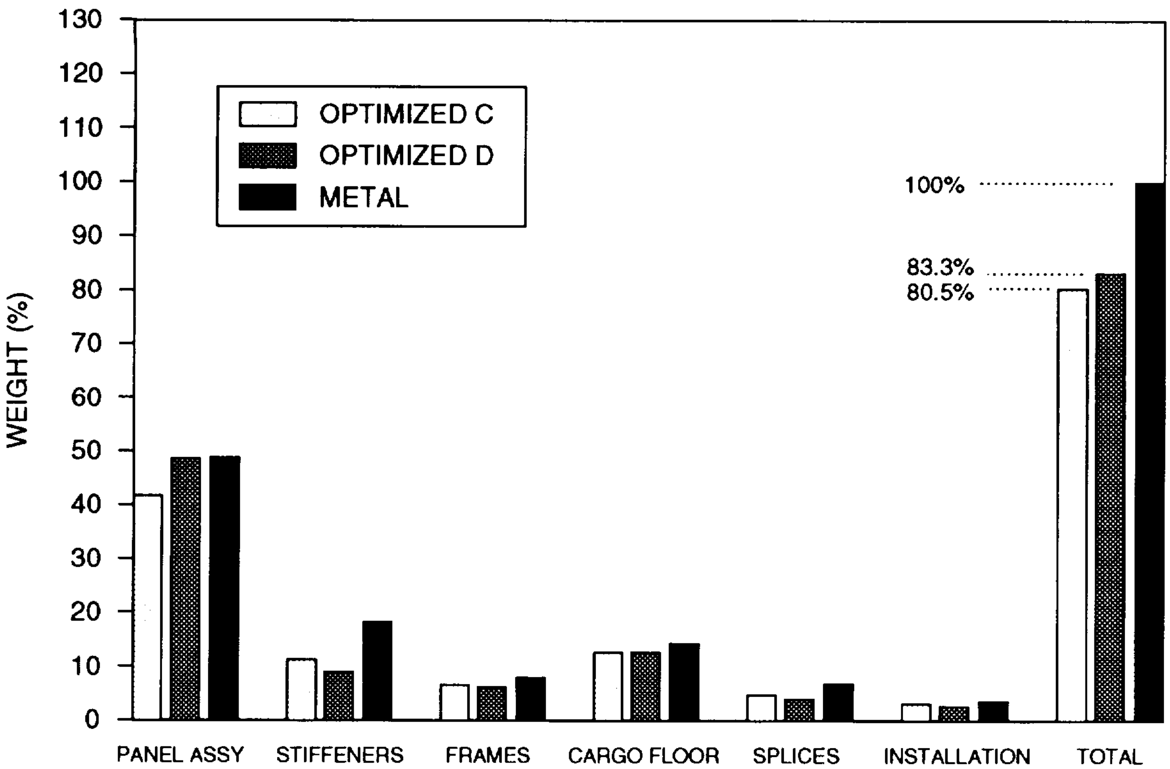

Figure 19: Weight Results for Globally Optimized Keel Designs

SELECTION RATIONALE

The cost and weight results of the globally optimized keel designs for each family are shown in Figure 20, along with results for the original four designs and the metal baseline. The sloped line reflects a typical performance value of weight.

The Design Build Team (DBT) approach was used to down-select to a single design family for keel panel local optimization. The down-select decision was based on both the cost/weight results reported above and the risk issues associated with each design concept. The risks related to manufacturing process development, performance development, and program demonstratability are listed in Table 2 for design families C and D.

One process risk for both families is the cure of thick laminates, although Hercules has had good success with laminates up to 3/4" thick. Most other process risks for Family D relate to the core: its machining, cleaning, and handling. Cleaning is an issue for both the C and D Design IML tools with their narrow slots. Tooling development for the C Family J stiffeners is another process risk item.

The performance risks for Family D again relate primarily to the core. Damage resistance, moisture ingression, and repair of thick skin and sandwich structure are all concerns. Design C performance also requires the development of thick skin repairs. The bonded elements of Family C carry risks associated with repair, durability, and damage tolerance, as well as load eccentricities in the areas of stringer runouts. If an OML tool is used for the Family C concept, achieving a high integrity bond between the stiffener and the stairstep ply drops becomes a risk.

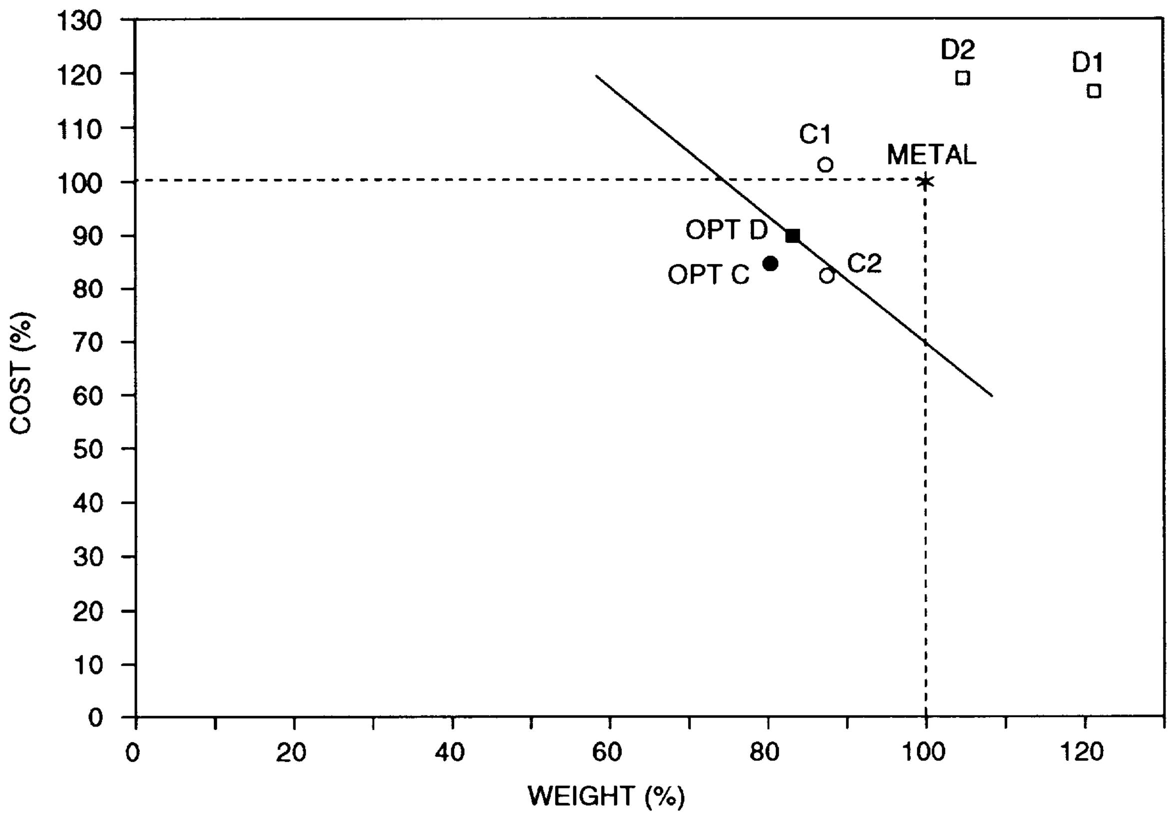

Figure 20: Cost/Weight Results Summary

Program risks result when the level of effort required to fully investigate certain technical issues threatens to outweigh the available resources of time, manpower, and budget. An example is the cost of an IML tool for the Family C concept which is considered to be prohibitively high for our demonstration purposes. This would require us to adapt an OML tool to simulate an IML tool, a task which is much more easily accomplished for the sandwich designs. Time is a factor in that many of the technical issues associated with the Design C keel concept have yet to be addressed. More effort has been expended to date on the Family D keel technical issues, however much core development remains to be done.

The cost and weight performances of the C and D Family designs were not greatly different. With this in mind, and after evaluating the relative risks of each concept, the concensus was that Family D would be selected for local optimization of the keel panel.

POTENTIAL FOR LOCAL OPTIMIZATION

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 during local optimization, as well as improvements in the manufacturing processes. A locally optimized design will also incorporate any developments in the understanding of the technical/economic issues identified during global evaluation.

Table 2: Risk Issues for Keel Design Concepts

	C FAMILY	D FAMILY
MANUFACTURING PROCESS DEVELOPMENT RISK	• Thick laminate cure • Cleaning of IML tool • Tooling for J stiffeners • Stringer splices	• Cure of thick laminate with tapered core • Machining, handling, cleaning of core • Cleaning of IML tool
PERFORMANCE DEVELOPMENT RISK	• Stiffener bond to stairstep ply drops w/ OML tooling • Durability and damage tolerance of bonded elements • Repair of thick skins • Repair of bonded stringers • Load eccentricities (stringer runout)	• Damage resistance of core • Moisture ingression • Repair of thick skin • Repair of sandwich, bondline • Core development
PROGRAM RISK	• Cost of IML tool is prohibitive for demonstration purposes • Schedule for working technical issues	• Core screening, development

Material costs are a major factor in the recurring costs. An optimum balance will be sought between material cost and performance, especially in the skins and core where the majority of the material resides. A toughened resin system has shown advantages for the keel skins; however, the degree of toughness can be altered to maximize compressive performance without unduly sacrificing the required tension damage tolerance for large crack scenarios. A wide variety of core materials will be screened to determine which can demonstrate the required stiffness, strength, and damage resistance while maintaining a low density. Foam core, honeycomb, in situ foam, fiber-filled foam, foam-filled honeycomb, and multi-layered syntactic foam are all being considered as candidate core structures for the keel panel. Both glass and graphite fibers of various layups will be evaluated for the honeycomb cores, as will thermoset and thermoplastic resins.

Major geometric variables to be considered include frame spacing, frame height and width, core thickness, and alternate cargo floor beam and stanchion cross sections. Major laminate variables include ply orientations, stacking sequences, and ply drop rates. COSTADE (References 3, 4, 5), a software design tool that incorporates cost and structural mechanics constraints with an optimization algorithm, will be used to support studies on the effects of material, geometric, and laminate variables. COSTADE was used during local optimization of the crown panel and will be further developed to support the keel design.

Several potential manufacturing improvements will be surveyed during local optimization of the keel. One area of potential improvement is the core fabrication. The results of the current core fabrication and performance trials could have a significant effect on the process used. Also, an investigation into the key process drivers of advanced tow placement as they relate to a highly tapered skin may yield higher efficiencies. Another cost-saving measure could result from removing the frame cap charge as was done in the ATCAS crown frames. The curing of the panel assembly could also see some processing improvements brought about by modified bagging and tooling approaches. The pultrusion process, which has a significant impact on the keel design, needs to be better understood in terms of both processing requirements and design/process interactions.

Insight gained from ongoing studies to understand associated technology issues will be incorporated into the design and analysis of the keel during local optimization. Included will be developments in analysis techniques (i.e., optimization procedures, residual strength analysis) and results from related test efforts (i.e., core strength, ply drop tests, fracture tests, impact damage resistance, material screening). Additionally, the structural criteria on which the analysis is based will be revisited to verify its applicability. For instance, the minimum stiffness requirement, which drives the skin thickness over much of the panel, was conservatively set at 90% of the baseline aluminum. If a lower value were acceptable, additional weight savings would be realized.

Figure 21 shows an estimate of the total potential cost and weight savings which may be realized as a result of the local optimization effort.

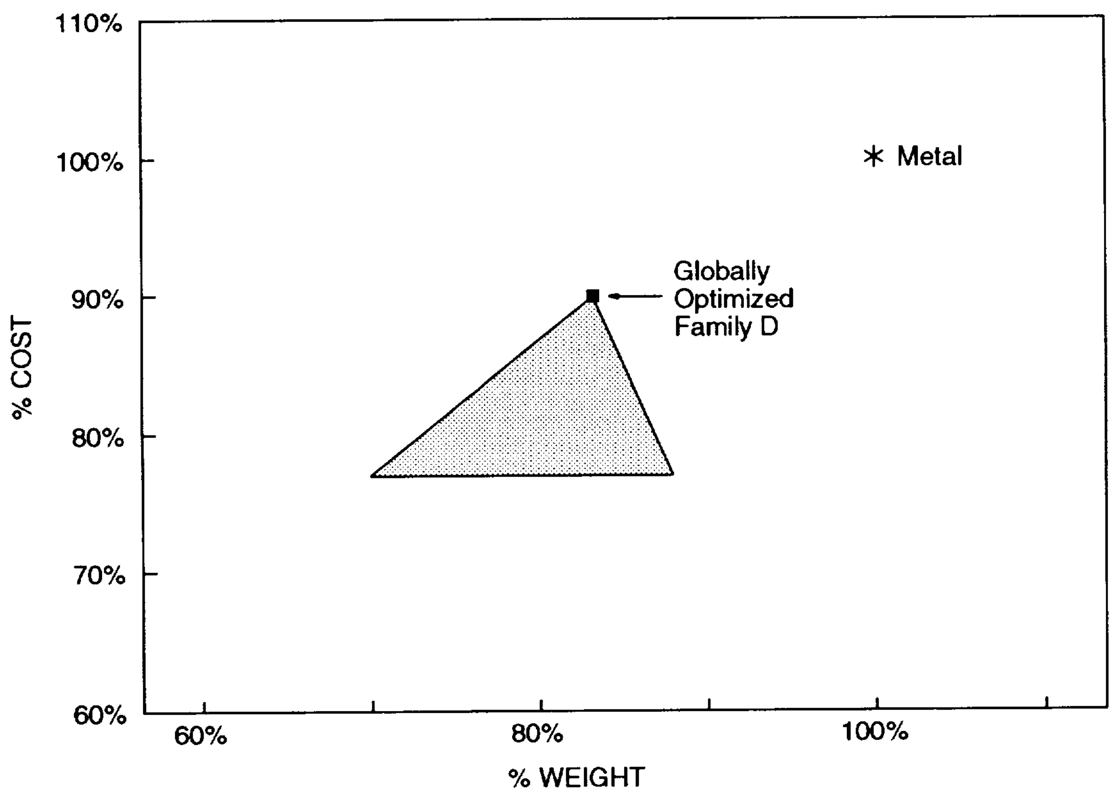

Figure 21: Local Optimization Potential

SUMMARY

Two designs from each of two families were developed for global optimization of the keel quadrant. Both Design Families C and D were considered in the study. Family C is a structural skin stiffened with bonded stringers and frames. Family D is a sandwich construction with bonded frames. Each design was sized considering critical load cases, damage tolerance, and attachment details. A detailed fabrication and assembly plan was developed for each design. These were then used to estimate weight, material costs, and labor rates.

Both recurring and nonrecurring (minus capital equipment) costs were estimated according to specific groundrules (e.g., 300 shipsets at a rate of 5 per month).

The designs within each family differed in material types, manufacturing processes, and structural variables. These differences helped to distinguish a range of cost and weight variation for each family. Design trades within a family yielded data on cost and weight centers, and helped to identify interactions between design variables. Such data is crucial to local optimization studies. Studying two designs per family also provides a convenient means of checking for errors in the cost estimating tasks (e.g., data entry, plotting) by analyzing the cost results and the differences between designs.

The majority of weight for all designs resides in the stiffened panel (skin and stringers/keel chords for Family C; facesheets, core, and intercostals for Family D). This is especially true in the forward end where gages are larger to accommodate the highly concentrated loads near the wheel well cutout. The skin gages in the more lightly loaded aft end tend to be driven by minimum skin buckling (Family C only), hoop tension damage tolerance, and/or the minimum stiffness criteria. Skin gages near panel edges are controlled by joint bearing and/or bypass requirements. The frames and cargo support structure were stiffness rather than strength designed and showed only a small weight advantage over the metal design.

Cost estimates for all designs revealed recurring costs to comprise over 90% of the total cost. For the composite designs, the labor and material portions of the total recurring cost are not dramatically different; the labor costs being only slightly greater. In the metal baseline however, labor costs are significantly larger than the material costs. Within a single design, the relationship between the labor and material cost components can vary widely for individual fabrication and assembly steps. For instance, panel bonding consists almost entirely of labor costs, while batch tow placement processing of skins is dominated by material costs. The breakdown of cost estimates to this and lower levels of detail is necessary in order to attack cost centers in local optimization.

Fabrication and assembly of the skin/sandwich panel and its stiffening elements is the largest cost component. Installation of the cargo floor frames and panel splices comprises another major cost center. The majority of the cost savings realized by the composite designs over the metal baseline result from the fabrication of the splice elements and the cargo floor structure.

As was the case in an earlier study of the crown quadrant (Reference 1), the switch to a high performance fiber to reduce skin weight was not found to be cost effective. This relates to the trade between a higher material purchase price and the costs saved from added performance capability. The economically acceptable increase in cost per unit weight savings was considered in this evaluation. Material cost and weight design trades such as performed in this keel study are useful in determining an acceptable increase in material cost per added performance. Note that these relationships are likely to be application specific due to differences in design drivers.

Design concepts for each family studied were globally optimized by mixing and matching the best design features, and by correcting any inconsistencies in the analysis and criteria applied to them. The globally optimized designs for both Families C and D include AS4/977-2 (toughened resin system), a panelized keel beam (as opposed to discrete keel chords), and a six stanchion cargo floor frame. Both designs are cost and weight competitive relative to the metallic benchmark, even though both of the original non-optimized Family D designs were heavier and more costly than the baseline. The optimized Family C design presented a 15% cost savings and 20% weight savings as compared with the metal baseline. The optimized Family D showed 10% cost savings and 17% weight savings.

Based on these cost/weight results, and an assessment of risks associated with each design, a single design family was selected for further study in local optimization. The risks in question relate to the development of manufacturing processes, performance characteristics, and the ability to demonstrate the chosen concept within the confines of program schedule and budget. Family C was judged to have the greater risk, due in large part to questions surrounding the durability and damage tolerance of bonded stringers, and due to the prohibitive cost of an IML tool for program demonstration purposes. The sandwich designs are more adaptable to an OML type process. In view of these risks, and the fact that the costs and weights of the C and D Family designs were not greatly different, Family D was chosen for keel local optimization.

Local optimization is planned to further refine Family D and attack cost centers identified during the global evaluation phase. Attempts to reduce material costs will include studies of skins with varying degrees of toughness. An extensive screening of core materials will also be conducted. A software design tool that includes cost and structural mechanics constraints for keel panels will be used to support optimization of design variables such as laminate and core thicknesses, ply orientations, and stacking sequences. The manufacturing approach to panel subassembly and the use of composite fasteners will also be evaluated. The local optimization effort will incorporate any developments in related technology studies. Advanced analysis techniques, test data, and refinements of the structural design criteria could all lead to improvements in the cost and weight results of the keel quadrant.

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Session VIII

DESIGN/ANALYSIS TECHNOLOGY

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