NASA Contractor Report 4736

Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE)

Overview

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Contracts NAS1-18889 and NAS1-20013
Prepared for Langley Research Center

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Prepared for Langley Research Center
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FOREWORD

This document is one of four complementary final technical reports on the development of a design cost model. The design cost model was part of a larger effort focused on composite technology development for transport fuselage structure. Therefore, most of the applications documented in this report relate to advanced composite designs and processes. The four reports comprising the final documentation for the design cost model include:

Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE)

- **Overview** (CR 4736). *Synopsis of COSTADE initiative, including integration of cost, weight, manufacturing, design, structural analysis, load redistribution, optimization, and blending.*
- **Design Cost Methods** (CR 4737). *Components of cost analysis and their interactions. Theoretical framework for process-time prediction. Methods for developing and maintaining cost equations. Applications to ATCAS quadrant designs.*
- **User's Manual** (CR 4738). *COSTADE user instructions, including hardware requirements and installation procedures. Program structure, capabilities, and limitations. Basis of cost model and structural analysis routines. Example problems.*
- **Process Cost Analysis Database** (CR 4739). *Rationale for database framework. Database user's guide, including capabilities and limitations. ATCAS process step equations.*

Work described in these reports was sponsored by the National Aeronautics and Space Administration, Langley Research Center (NASA-LaRC) as part of the contracts NAS1-18889 and NAS1-20013, Task 2. The Boeing Commercial Airplane Group, Seattle, Washington, was prime for these contracts, which were performed from May 1989 through December 1995. Both contracts were funded by the Advanced Composite Technology (ACT) program. Boeing's ACT program was called Advanced Technology Composite Aircraft Structures (ATCAS). Direction from NASA-LaRC specific to ATCAS design cost model development was provided by J.G. Davis and W.T. Freeman.

At completion of these contracts, Boeing program management included Bjorn Backman as Program Manager, Peter Smith as Technical Manager, and Larry Ilcewicz as Principal Investigator. Authors listed for this contractor report prepared portions of the document. The members (past and present) of the Boeing ACT contract team who contributed to the work described in this document include:

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1.0 ABSTRACT

Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE) is being developed as a tool to support design build teams in their efforts to achieve cost effective and feasible commercial aircraft composite fuselage structure. COSTADE is a multi-disciplinary evaluation and optimization tool that includes cost, weight, design, stress, and manufacturing modules. Fabrication costs are included early in the structural development process allowing the identification of cost-weight sensitivities. The use of this tool also reduces engineering development costs by shortening design cycle times and by providing improved starting points for more detailed evaluations.

This report presents details of the COSTADE development effort, descriptions of the major modules included in the software, and applications illustrating its use on the Advanced Technology Composite Aircraft Structures (ATCAS) program.

2.0 INTRODUCTION

The rate of application of composites to primary commercial airframe structure has been slow. Composite materials are an obvious choice for weight reduction, corrosion resistance and fatigue suppression but before bold leaps toward more extensive use of composites can be expected in commercial airframe applications, their costs (especially fabrication costs) must be reduced. Accurate, reliable prediction methods for production costs of composite structures must be demonstrated. The Advanced Composite Technology (ACT) Program's goal is to establish design concepts, develop manufacturing approaches, and demonstrate the structural integrity and cost effectiveness of innovative low cost composite assemblies, providing confidence for production commitment to primary structure by the turn of the century (Ref. 1).

This initiative is part of the NASA/Boeing Advanced Technology Composite Aircraft Structures (ATCAS) program. The objective of the ATCAS program is to develop an integrated technology and demonstrate a confidence level that permits the cost and weight-effective use of advanced composite materials in commercial transport fuselage structures.

The overall goal of the COSTADE development effort is to accurately predict and enable the reduction of the cost of composite structures for advanced technology use in future production applications. The costs addressed have been: fabrication, and design and analysis costs. The original concept for COSTADE is presented in Ref. 2.

Fabrication costs have been predicted early in the structural development effort by tailoring designs to the selected processes. The fabrication cost model developed as part of ATCAS is an equation driven, semi-automated detailed estimating method.

Operating costs have been addressed initially by allowing cost/weight trades to be quickly performed early in the structural development effort. Design/Build Teams (DBTs) often trade lower fabrication costs for increased weight (and vise versa) by considering the value of weight saved in a structure. COSTADE has the ability to perform this type of cost/weight trade. The actual calculation of operating costs is not part of the software.

Design and analysis costs are being reduced by enabling multi-disciplinary analysis and optimization to quickly perform preliminary sizing of practical designs. The ability to tailor composite materials has always appeared attractive to design engineers. Numerous material, laminate, and process variables can be considered when designing advanced composite materials for specific applications. However, it may be argued that this attribute has also slowed the application of advanced composite technology. COSTADE software provides a tool to allow DBTs to develop better designs more efficiently with reduced design cycle time.

More detailed objectives of COSTADE are listed in Table 2-1.

Objectives	Approx Effort ($) %
1. Understand Design Details Critical to Manufacturing Costs	20
2. General Theoretical Framework, Good for Current and Evolving Processes	15
3. Design Constraints to Quickly Evaluate Concepts for Structural Performance	15
4. Constrain Selection of Design Details that Affect Manufacturing Tolerances	5
5. Cost-Effectively Blend Design Details Over Variations in Load	10
6. Develop Software (COSTADE) to Quickly Perform Design Trade Studies	15
7. Verify the Design Cost Model Using ACT and Past Databases	20

Table 2-1. Objectives for design cost model development and verification.

COSTADE is presently used to evaluate and refine structural designs from the freezing of loft lines (external configuration) and manufacturing processes until the structural components are sized. The resulting designs therefore are tailored to the manufacturing processes. Once the design is sufficiently refined, other more detailed analyses (not part of COSTADE) can perform final evaluations if necessary. These other analyses may include non-linear finite element models.

COSTADE contains a set of analyses from the major groups affecting the structural design as shown in Figure 2-1. By including a cost model in a multi-disciplinary optimization tool, costs for *feasible* designs are predicted.

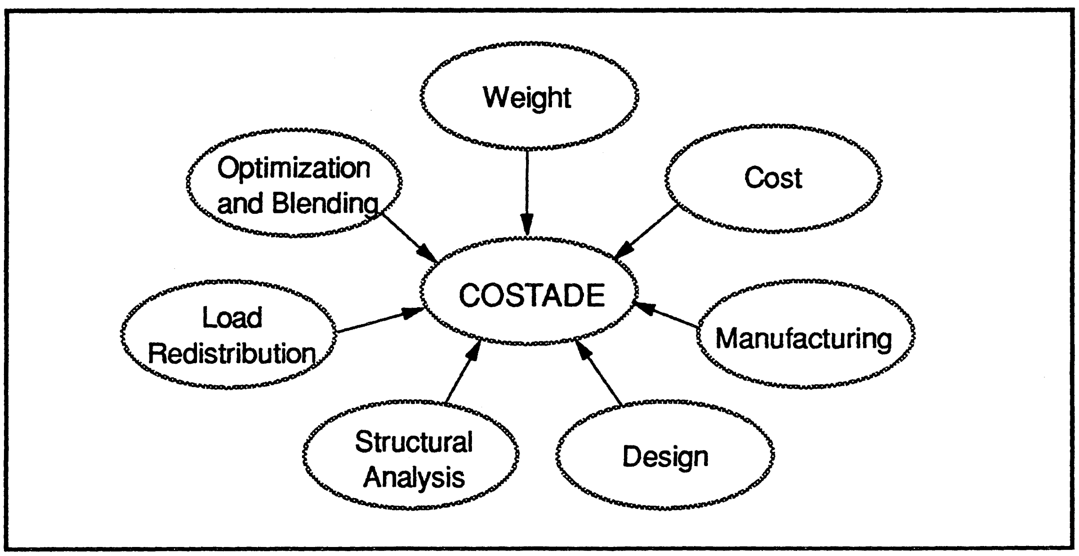


Figure 2-1. Major analyses represented in COSTADE.

COSTADE has been developed at the Boeing Commercial Airplane Group (BCAG) in coordination with a number of subcontractors including Sikorsky Aircraft, Northrop/Grumman, University of Washington (UW), Massachusetts Institute of Technology (MIT) and Dow/United Technologies. The primary developers and their roles are shown in Table 2-2.

	Cost Model	Structural Analysis	Manufacturing Constraints	Optimization Algorithms	Software Frame-work
Boeing	X	X	X		X
UW		X	X	X	X
Sikorsky	X	X			
Northrop	X	X			
MIT	X				
Dow/UTC	X				

Table 2-2. Major contributors and responsibilities for COSTADE.

The use of DBTs, combining multi-disciplinary talents to address critical issues, form the basis of the ATCAS approach. COSTADE enables DBTs to efficiently use the available manufacturing and structures databases for cost-effective design. COSTADE allows a DBT to quantify and explore the complex interactions associated with aircraft structural design criteria, fabrication cost, manufacturing constraints, and structural weight. This single software tool combines the analyses used by each group contributing to the final design.

The COSTADE design tool is intended to be suitable for several applications. First and foremost, it gives timely support to a DBT by efficiently projecting the effects of preliminary design decisions on manufacturing costs. Calculations performed during sizing exercises will be matched with an approximation of the effect of structural details on process costs. The software can help the DBT quickly trade cost and weight of numerous design details prior to concept selection. This enhances the DBTs' ability to select design variables (e.g., stiffener spacing, material type, skin gage) that; (a) are cost effective for available manufacturing processes, and (b) meet performance requirements for the particular application. As with any software, the accuracy of COSTADE predictions are dependent on data input by the DBT; therefore, the cost and weight savings potential will increase as composite databases grow.

Other applications include trade studies to guide research and development (R&D) programs in manufacturing, structures, and materials. One example for use in manufacturing R&D is to help determine if the acquisition cost of advanced equipment and facilities is offset by enhanced efficiency. Relationships between structural design guidelines, criteria, and manufacturing cost can be used to judge which areas should be studied in greater detail to avoid the unnecessary costs associated with overly-restrictive design rules. Trade studies may also be used to estimate what added material cost is acceptable for enhanced performance.

The ATCAS program is studying a commercial wide body constant diameter fuselage section just aft of the wing-to-body intersection and main landing gear wheel well. This section has a fuselage diameter of 244 inches and is approximately 80% of the size of a 747. The ATCAS fuselage section is divided into four circumferential segments, crown, left and right sides, and keel. Figure 2-2 illustrates the fuselage section and the three final COSTADE models used in ATCAS phase B.

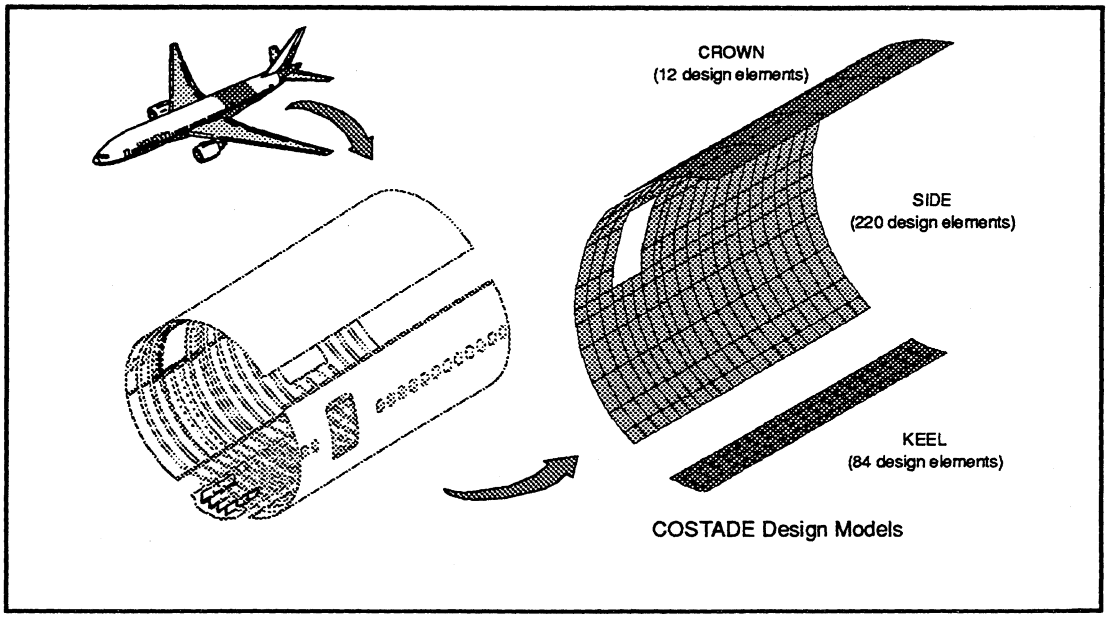


Figure 2-2. Major phase B COSTADE models.

Applications of COSTADE to ATCAS phase B structure is documented in this report for the development of crown, keel and side fuselage structures. Applications of the cost model to the ATCAS phase B baseline full barrel is also included in this report.

This report is an overview of the COSTADE initiative. Three other closely associated reports document more details of this initiative. Ref. 3: COSTADE - Design Cost Methods presents the fabrication cost model development and detailed applications to ATCAS phase B structures. Ref. 4: COSTADE - User's Manual is a user's manual for the COSTADE software. Ref. 5: COSTADE - Process Cost Analysis Database is a user's manual for the relational database used to manage cost data.

3.0 DESIGN REPRESENTATION AND BLENDING ALGORITHMS

The analysis modules in COSTADE require a design to evaluate. If optimization is performed, various modified designs are evaluated and compared. Several structural configurations are available including: skin/stringer configurations with hat, blade and J stringers, and sandwich. Several circumferential frame cross-section geometries are also available. Discrete design elements are defined to model load gradients.

A panel is modeled by dividing it into discrete design elements in order to account for the varying loads and designs throughout the panel. The geometry and loading condition for a design element are assumed constant throughout the element. Design element rows and columns are shown for a four row, five column model in Figure 3-1. These row and column numbers are used to locate each element with regard to its neighbors so that blending can be effectively performed. Cost, weight, and margin of safety calculations are made assuming all ply drops occur at element boundaries. The magnitude of the load gradients, and as a result the geometry gradients, dictate the mesh density required to adequately model the panel. All design elements are assumed rectangular in shape, and the panel as a whole is rectangular. This requirement may need to be eliminated, in the future, in order to model more general structural shapes. A 220 element model (11 rows and 20 columns) used for the sandwich side panel is shown in Figure 3-2.

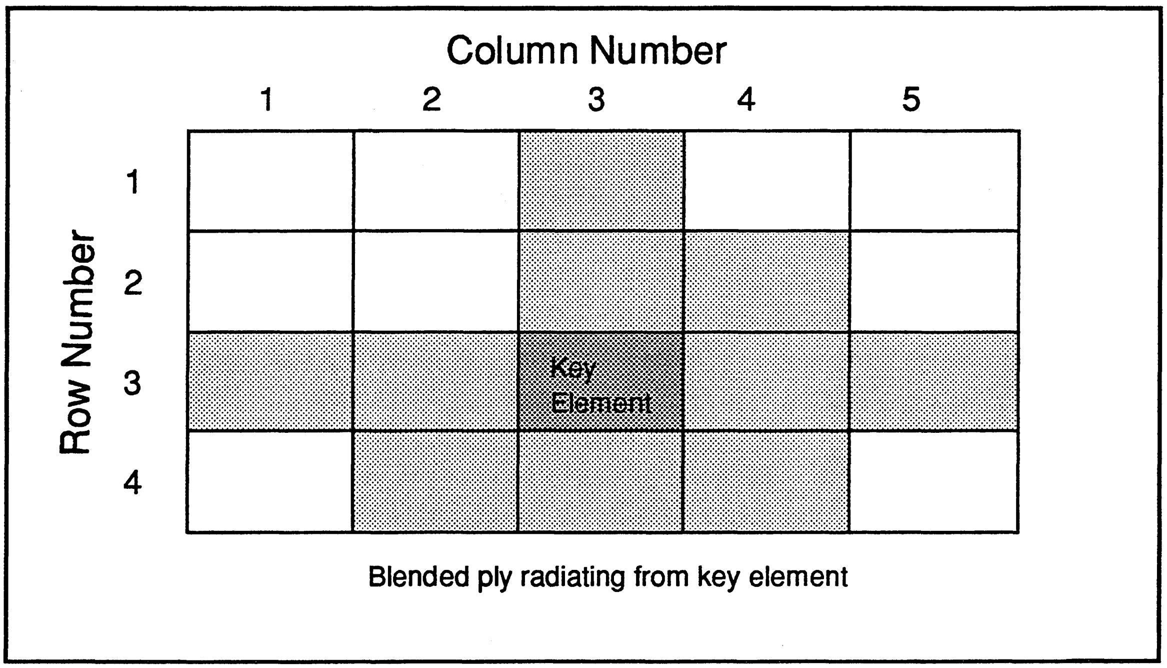


Figure 3-1. Design element row and column designations.

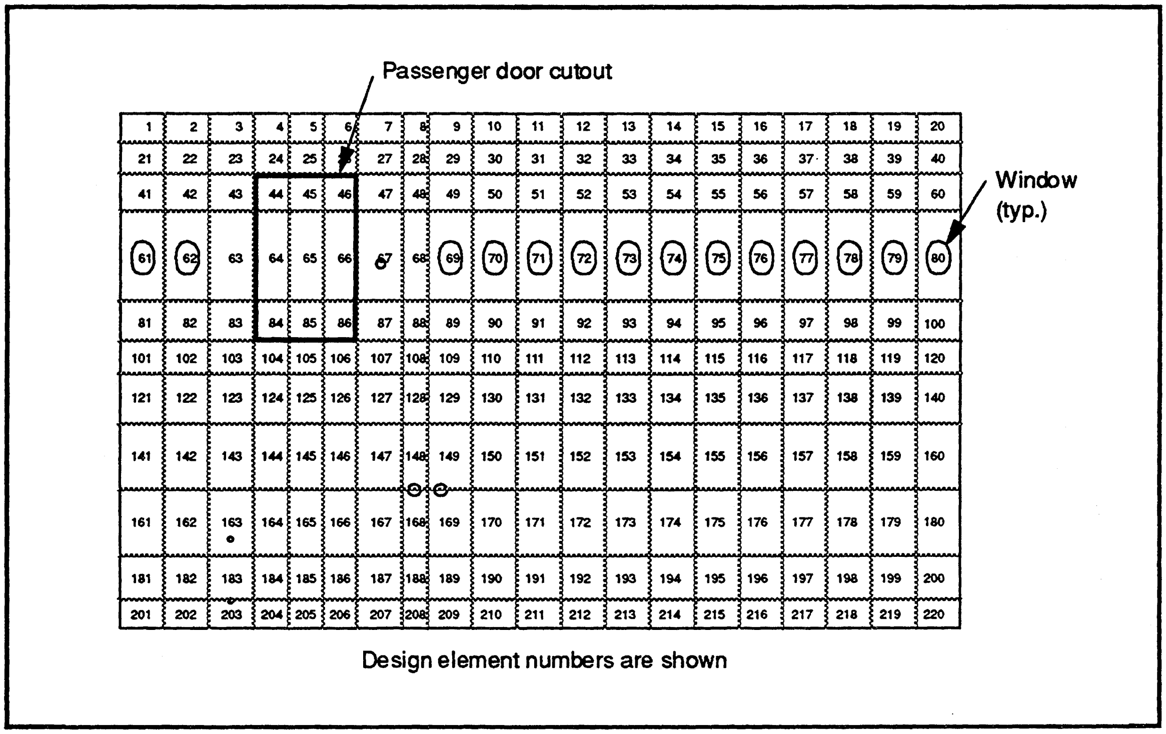


Figure 3-2. ***220 design element representation of a sandwich side panel.***

A blending function is included, allowing for controlled ply drops and geometry changes over the surface of the panel. References 6 through 10 document the development of these algorithms.

The structural analysis methods in COSTADE evaluate point load conditions for constant geometry sections. Element size is selected to represent an area over which the point load structural analysis approximations are reasonable. Non-blended optimization of several points on a panel, having load gradients across the surface, can lead to local designs which are discontinuous. In order to globally optimize a panel, individual point designs must be "blended". The blending rules in COSTADE constrain the design to regions of the design space which maintain structural continuity across element boundaries. Blending, crucial to cost analysis based on a continuous panel design, has traditionally been the responsibility of the design engineer. However, due to the vast number of possible design configurations, this task becomes very difficult for composite structures even with the help of computer tools. This was experienced in local optimization of the ATCAS crown panel before a blending algorithm was added (Ref. 11). Similar studies performed with the ATCAS crown panel after a blending algorithm was installed took significantly less time (Ref. 12).

The COSTADE blending algorithm imposes a set of cost, manufacturing, and structural feasibility constraints on a set of point designs. Blending rules are applied to all geometry variables in the problem: fiber angles, ply thickness, core thickness, stringer cross section and spacing, and frame cross section and spacing, and are closely tied to the manufacturing processes being considered. For example, pultruded stringers require a constant cross section (no tapers along the length), so the blending rules for the stringer must constrain the design definition accordingly. As a second example, batch processing of frames may require that all frames are identical, and manufacturing issues may dictate a near constant radius of curvature. Blending rules must be applied to both the frame cross section and panel thickness (to maintain a constant radius of curvature inner mold line, IML) so as to minimize frame variation.

Blending rules are defined on a ply by ply basis for laminate variables, and for all stringer and frame geometry variables, in each design element. Generally, the blending rule for a single variable will be the same in all elements, however, this is not a strict requirement. A variable is defined as either "unblended" or "blended". In the unblended category, two options are available, FIXED or FREE. The FIXED option prevents any changes to that variable during the optimization process. The FREE designation allows variables to change during optimization with no blending constraints. Options available in the blended category are documented below. Blending rules require the definition of a key element for each variable. All blended variables in non-key elements are controlled in some sense by the key element.

Section 8 of this report and References 12 through 15 show the use of the blending algorithms in practical structural design efforts.

3.1 Laminate Blending Rules

A basis laminate is defined for the panel, and the layup in each design element is formed by some subset of the basis. Blending rules for ply angles and thicknesses control the degree of change across element boundaries. Blending rules are applied to the ply angles, ply thicknesses, and core thickness independently.

3.1.1 Ply Design Rules

Ply design rules are defined for each ply in the skin and stringer laminates. Skin and stringer stacking sequences are defined separately but in a similar manner. The rules allow the user the following options for each ply in the laminate: non-symmetric, symmetric, balanced and symmetric, and balanced.

The non-symmetric design rule affects no other plies in the laminate. The symmetric design rule forces the ply on the opposite side of the laminate mid plane to have the same orientation and ply thickness. The balanced and symmetric design rule forces a balanced ply on the same side of the laminate mid plane with up to one other ply between the balanced plies, and symmetry imposed on the opposite side of the laminate mid plane. The balanced design rule forces a balanced ply on the same side of the laminate mid plane with up to one other ply between the balanced plies, or a balanced ply on the opposite side of the laminate mid plane. Symmetry is not imposed in this case.

Frame laminates are simply represented by one zero degree ply of variable thickness for each frame element.

3.1.2 Ply Angle Blending Rules

Ply angle blending for skin laminates is accomplished using blending rule LAM-A-1. This blending rule requires that the angle for ply *n*, in each element, is the same as the angle for ply *n* in the key element (there is one key element per ply). Laminate changes between elements are a result of ply drops from the key elements.

Ply angle blending for stringer laminates is also accomplished using blending rule LAM-A-1. In the case of a stringer this blending rule requires that the angle for ply *n*, in each element in a stringer row, is the same as the angle for ply *n* in the key element in that stringer row (there is one key element per ply for each design element row). Note that blending rule LAM-A-1 (and LAM-T-1 and LAM-D-1 below) will produce generally distinct stringer definitions, and care must be taken that the fabrication costs represented in the cost equations are valid for this condition.

3.1.3 Ply Continuity Blending

Ply continuity blending can be used for laminates. The rules dictate that once a ply has been dropped it may not be added back into elements which radiate away from the key element, as shown in Figure 3-1. The use of multiple key elements allows users to control multiple padup areas throughout a panel. The blending rules produce a quasi-convex ply shape across the surface of the panel with no disconnected regions. There are two blending rules available in COSTADE to do ply continuity blending, those are ply blending based on ply thickness variables, LAM-T-1 and ply blending based on ply distance variables, LAM-D-1. These rules are explained in more detail below.

Ply Thickness Blending Rules.

Ply continuity blending for skin laminates can be accomplished using ply thickness variables, a blending rule called LAM-T-1. Blending rule LAM-T-1 uses "thickness variables", *t*'s to denote if a ply is present in an element or not. The variable $t = 0$ if a ply is dropped and $t = 1$ if a ply is present. Ply thickness blending for stringer laminates is also accomplished using blending rule LAM-T-1. A key element is defined for each ply in each design element row. Once a ply has been dropped from a row, it may not be added back into that row. A generalization of the thickness blending rule is to allow t to take on discrete values, such that t is between zero and some maximum number of plies, t_{max}. In this case $t = n$ means that n plies of the same fiber angle are adjacent in an element. However, most often the thickness blending rule is used with $t = 0$ or $t = 1$.

Ply Distance Blending.

Ply continuity blending for skin laminates can also be accomplished using ply "distance variables", a blending rule called LAM-D-1. Using the LAM-D-1 rule considerably reduces the number of design variables from using LAM-T-1 in the problem and therefore speeds up the optimization process. Blending rule LAM-D-1 uses "distance variables" *d*'s to denote the presence of plies. The *d*'s radiate away from the key element and take on integer values and denote how many elements in a row a ply occupies. For instance $d = 3$ means that the ply extends over three elements.

3.1.4 Core Thickness Blending Rules

Three options are available for the core thickness variables. The first option, LAM-C-1, sets the core thickness in non-key elements at a value which will result in a constant overall panel thickness (Rule LAM-C-1 is associated with identical frames along the panel length, with a constant radius of curvature). Blending rule LAM-C-2 sets the core thickness in non-key elements at a value which will result in a constant panel thickness in each row of elements (Rule LAM-C-2 is associated with identical frames along the panel length). Blending rule LAM-C-3 sets the core thickness in non-key elements at a value which will result in a constant panel thickness in each column of elements (Rule LAM-C-3 is associated with constant radius of curvature frames). The core thickness blending rules address cost model equation assumptions (i.e. identical or distinct frames), and manufacturing issues which dictate a constant radius of curvature.

3.2 Stringer Geometry Blending Rules

Two options are available for stringer geometry variables. Blending rule STRG-G-1 forces all the stringer geometry variables in all elements to be identical over the whole panel. Blending rule STRG-G-2 forces the stringer geometry variables in a row to be identical for all elements in that row. Blending rule STRG-G-2 produces stringers that have a constant geometry along their length, but generally different stringers around the circumference of the fuselage.

3.3 Frame Geometry Blending Rules

Two options are available for frame geometry variables. Blending rule FR-G-1 forces all the frame geometry variables in all elements to be identical over the whole panel. Blending rule FR-G-2 forces the frame geometry variables in a column to be identical for all elements in that column. Blending rule FR-G-2 produces frames that have a constant geometry along their length, but generally different frames along the axis of the fuselage.

4.0 FABRICATION COST MODEL

4.1 Cost Model Goals

The fundamental requirements of the cost model are the abilities to:

1. predict fabrication costs for designs and processes for which production data are available
2. predict fabrication costs for advanced technology designs and processes for which directly applicable production data are not available
3. evaluate a range of advanced designs based on modifying variables normally specified on engineering drawings and
4. be refined over the course of the structural development effort.

The above requirements of the cost model allow fabrication costs to be addressed early in the structural development effort, designs to be tailored to the chosen processes, and continuous refinement of the predictions, based on new data or insight, to occur.

4.2 Implementation at Boeing

References 3, 13, 14 and 16 through 20 detail developments of the ATCAS cost model. The cost model being developed as part of ATCAS is an equation driven, semi-automated detailed estimating method.

The detailed cost estimating process is performed as follows:

1. identify a design
2. prepare a manufacturing plan
3. make estimates for each process step in the manufacturing plan
4. sum up the costs for each process step in the manufacturing plan.

Traditional detailed estimating has advantages and disadvantages. One advantage is this method's ability to be quite accurate if done well. Another is that it can be performed without production data. Historical drawbacks include:

1. high man-hours and flow time to perform the estimating task using non-automated methods
2. frequent inconsistency between estimates and/or estimators and
3. inadvertent omission of steps from the manufacturing process.

By automating the procedure using relational databases the first two drawbacks are fully addressed and the third drawback is partially addressed. By preassembling major process plans, the time to develop the factory manufacturing plans for a new design is reduced. Consistency between the plans for alternate designs is also improved.

Writing equations for each process step allows the identification of parameters and part definition values controlling cost. The use of equations also allows the cost model to be embedded in multi-disciplinary evaluation/optimization activities.

4.3 Manufacturing Plans

Development of the factory begins by identifying the major process centers to be used for a particular design. A process center typically represents a location within a factory where a sequence of related process steps is performed. An efficient sequence of major process centers selected for the baseline ATCAS fuselage produces the factory flow outline shown in Figure 4-1. The assignment of facilities and equipment to particular areas produces the factory layout defined in Figure 4-2.

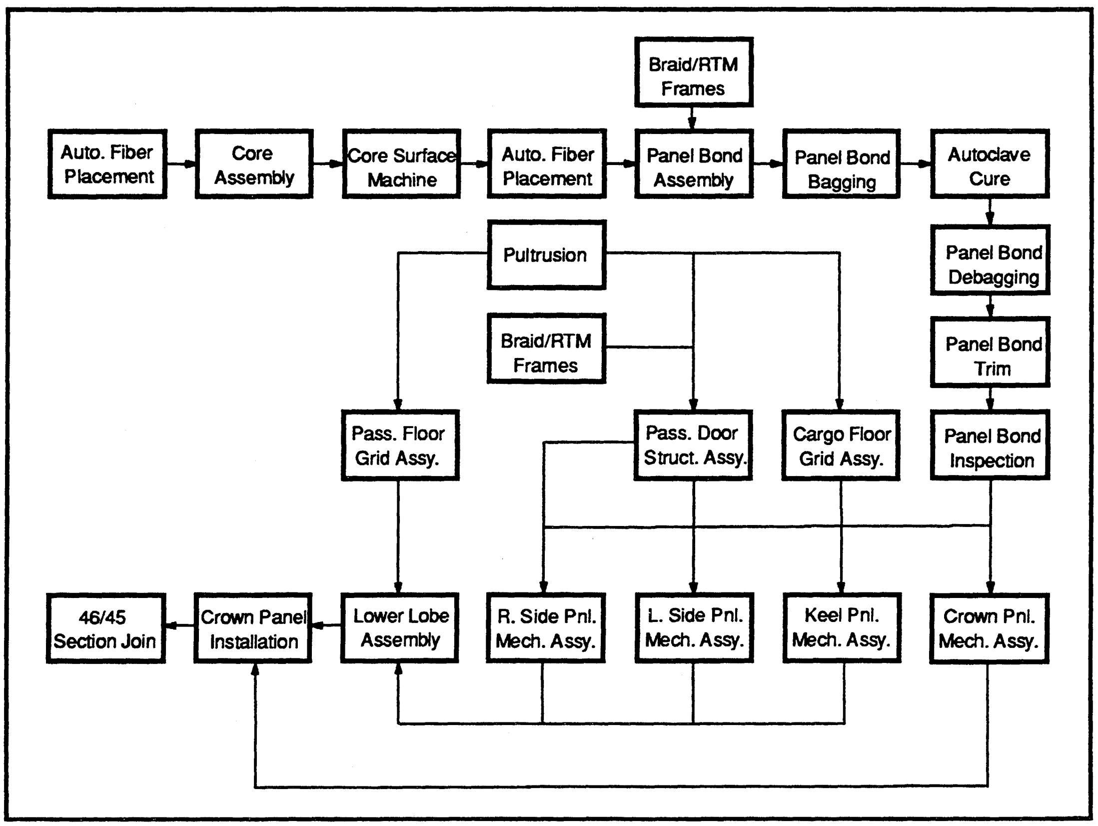


Figure 4-1. Factory flow outline.

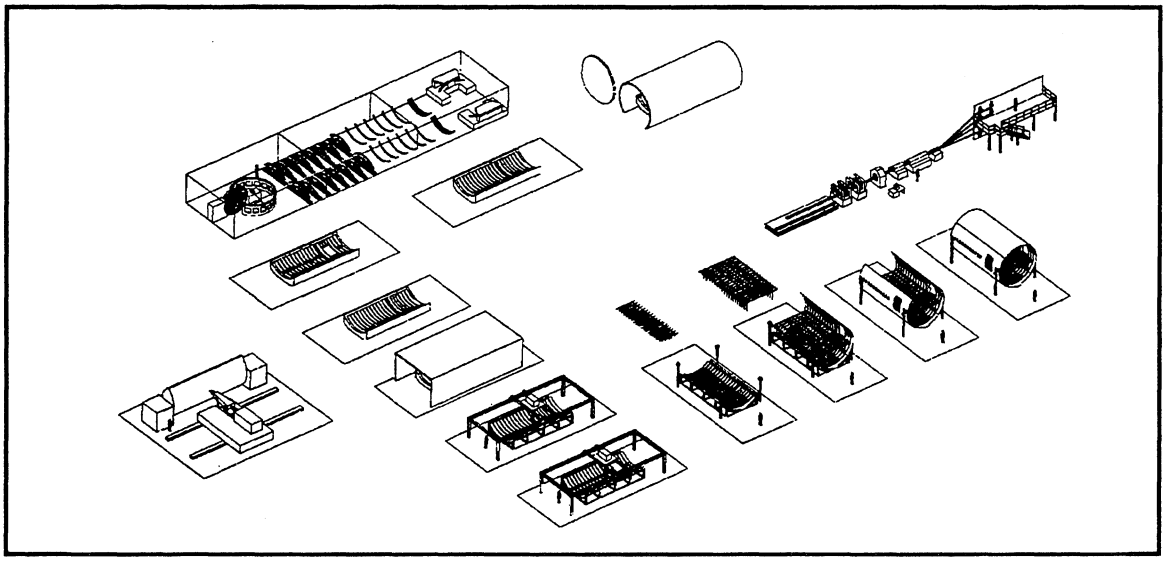


Figure 4-2. Factory layout.

The next level of factory definition outlines the process steps occurring at each process center. Each process step can be modeled as a manufacturing entity that requires inputs from other manufacturing entities (i.e. outputs *of* other manufacturing entities) and resources applied within the modeled entity as shown in Figure 4-3. The fabrication costs are found by summing the consumed resources within all manufacturing entities.

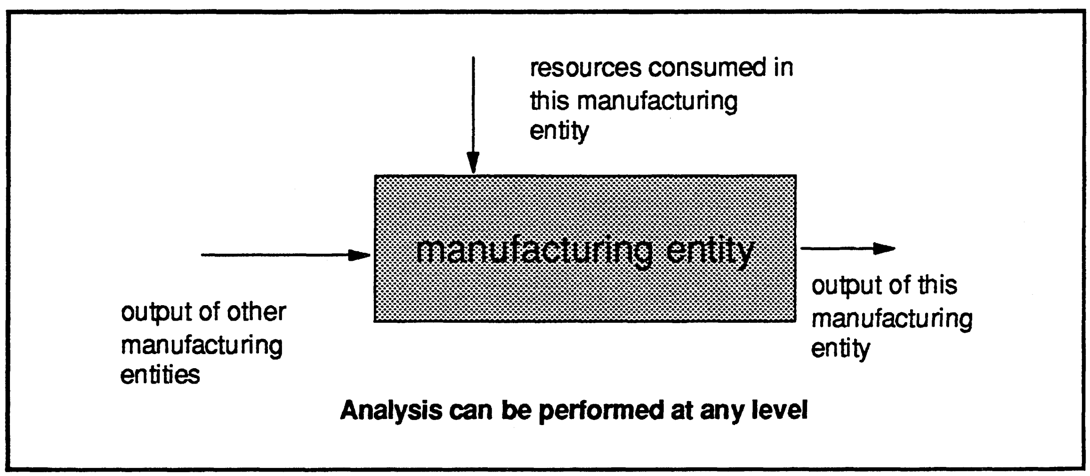
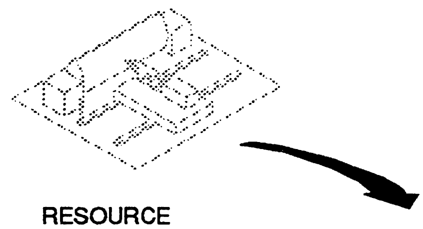


Figure 4-3. Single manufacturing entity.

A breakout of steps in the Automated Fiber Placement (AFP) process center is shown in Figure 4-4.



RESOURCE		PROCESS		PART
FACTORY	AREA	STEP	PROCESS STEP DESCRIPTION	PART NUMBER
1	2	10	Identify required items	261X0401-1
1	2	20	Clean OML cure tool surface	261X0401-1
1	2	30	Apply parting agent to OML cure tool surface	261X0401-1
1	2	40	Hand layup fabric ply over OML cure tool	261X0401-1
1	2	50	Position skin debulk bag	261X0401-1
1	2	60	Debulk hand layed up fabric ply	261X0401-1
1	2	70	Remove debulk bag from skin	261X0401-1
1	3	80	Setup AFP equipment for skin layup	261X0401-1
1	3	90	Layup skin using AFP equipment	261X0401-1
1	3	100	Reload prepreg tow onto AFP equipment as required	261X0401-1
1	3	110	Position OML cure tool into AFP cell	261X0401-1
1	3	120	Transfer skin from winding mandrel to OML cure tool	261X0401-1
1	3	130	Remove OML cure tool with skin layup from AFP cell	261X0401-1
1	1	140	Protect skin on OML cure tool	261X0401-1
1	1	150	Identify skin on OML cure tool	261X0401-1
1	1	160	Transport OML cure tool to core assembly cell	261X0401-1

Figure 4-4. Automated fiber placement process steps.

A complete manufacturing plan is presented as a series of process steps, outlining flow within and between all process centers. This manufacturing plan is based on the level of understanding of the processes. A more complete understanding generally results in the use of more (detailed) process steps. The number of steps will generally increase as the design matures. Each step is generally independent from others and therefore has different controlling cost and part definition values.

The factory area code (e.g. see Figure 4-4) corresponds to a physical location in a company's production system. Resource requirements such as personnel, capital equipment, inventory, facilities, energy, etc., will depend on the combined efficiency of process cells addressing specific design details. Delays or inefficiencies within any center can have a synergistic effect which may be overcome in time through design change, technology advancement or reallocation of resources. Complex interactions exist between factory flow and design traits. As the factory matures over time, cost equations must be updated to guide design development towards efficient use of the available factory.

Because the cost predictions are only as good as the manufacturing plans, extra care must be taken to ensure that no major steps are overlooked.

4.4 Process Step Equations

The manufacturing processes considered on the ATCAS program are those associated with low fabrication costs. They include the following processes: automatic fabric layup, automated fiber placement, hand layup, core fabrication, hot drape forming or roller forming, bag/cure, 2-D braiding, resin transfer molding, injection molding, pultrusion, thermoplastic forming, thermoplastic extrusion, part trim and deburr, titanium machining, aluminum machining, part wrap/protect, panel bond assembly, and mechanical assembly.

The fabrication costs for the resources consumed within many process steps depend on the time for the process step to occur. Resources such as recurring labor are of this type. Some non-recurring resource costs such as capital equipment, facilities and tooling can be accommodated (or allocated) in this way by calculating a cost on a time of use basis. The cost equation form for these types of process steps is:

*Fab Cost = (Manufacturing Process Step Time) * (Manufacturing Time, Resource Cost Relationship)*

Non-recurring costs can be accommodated in various ways as outlined later in this report.

Cost equations for non time related resources consumed in process steps are developed based on the physical relationships governing the resource consumption. For example the material placed during a fiber placement process (recurring material) may be purchased by the pound from a supplier. The cost equation for the material therefore would be dependent on the purchase price, receiving inspection, scrap and quantity of material successfully placed but not on the time taken to actually lay down the material.

4.4.1 Manufacturing Process Step Times

For process steps which require extensive use of manual labor, historical manufacturing data and time studies are required. Generally manual labor is difficult to predict, and the data collected must be treated to account for conditions such as non value added time and efficiency differences between workers. Narrowing the scope of the time study to particular process steps is a useful estimating approach. The predictions may represent the ideal production scenario and worker. A comparison of predictions versus actuals is used to arrive at the historical variance to the ideal conditions. A cost model equation is developed through selection of critical design parameters, (surface area, length, width, quantity, etc.), and a cost equation functional form, which best represent the physics of the problem for a range of likely structural details. The coefficients for a particular equation form are found based on the physics of the problem and available data.

The time taken for a manufacturing process step to occur is necessary for the bulk of process steps studied on the ATCAS program. The rigorous time studies routinely performed on production processes are seldom applied to developmental processes. The relevancy of data captured in a test or laboratory environment as it applies to production experience is often questionable. This can be due to the numerous differences in tooling concepts, drawing specifications, quality control techniques, and the experience of the people performing the processes. Considering this lack of a significant process database and supporting cost analysis, it is difficult to predict cost effectiveness with a high degree of confidence prior to production commitment is difficult.

Therefore time studies of new process technologies, with as few differences as possible from the anticipated mature production techniques, are desirable. Time studies performed in the production environment have greater fidelity and hence have a more credible predictive capability. Studies performed during the development phase typically reveal the process constraints, and are crucial in determining the tooling and equipment quantities needed for production. These studies can provide valuable insight into the relative cost effectiveness between particular designs and their associated processes. Furthermore, since this information is gathered during the product development phase, it has greater potential leverage on the ability to optimize the total production cost. For example, it can expose process sensitivities to the designer as critical decisions are being made. As production data becomes available, design cost models need to be updated to better represent an understanding of the company's investment in selected processes.

Historically, curve fits of existing data using power law equation forms have been the basis of numerous cost models. If data is available for curve fitting to and the appropriate variables are identified, this method can provide credible extrapolation capabilities. As an improvement on this method, the development of scientifically relevant equation forms was undertaken as documented in Reference 3. "Extensive" and "positioning" type process equation forms have been developed. The use of scientifically sound equation forms with coefficients having physical meaning has several advantages. First the required coefficients may be estimated *without time studies data*. Of course data of some kind is required to estimate the coefficients, but engineering models reduce the data needs. For example, when estimating the time required to drive across the country, the times taken for vehicles that had previously made the trip could be used as a basis for prediction. Another approach is to use a scientific model (e.g. well known mass, displacement, velocity, acceleration relationships) as well as some data (e.g. vehicle and driver performance characteristics, speed limits, distance to be traveled). Since the coefficients for a scientific model have physical meaning they may be able to be measured independently or compared with known coefficients for similar processes. The cost model development on the ATCAS program has attempted to follow the scientific approach described.

Scientific models are readily available for process steps that are understood. Typically there is no need to develop new ones since engineering textbooks from the various disciplines have numerous models. In cost estimating one's interest is often limited to predicting the time required. Scientific cost estimating methods require an understanding of the processes used. The equations developed were typically limited to the processes modeled. For example, waxing a car by hand is a different process than waxing a car with a buffer.

If the process chosen depends upon the quantity of output required, care must be exercised not to extrapolate beyond the point where one would change the process. For example consider two acceptable processes for performing a task. Process A has a small set up component (i.e. y intercept) and a moderate rate. Process B has a higher set up component but a higher rate. As shown in Figure 4-5 process A would be better for small output quantities (i.e. output < 5), process B would be better for high outputs. The use of the equation for process A in the domain where process B would have been a better choice, results in over predictions of times. This type of problem can occur when using non production data (often small output) to predict production scenarios if the processes used are not fully understood.

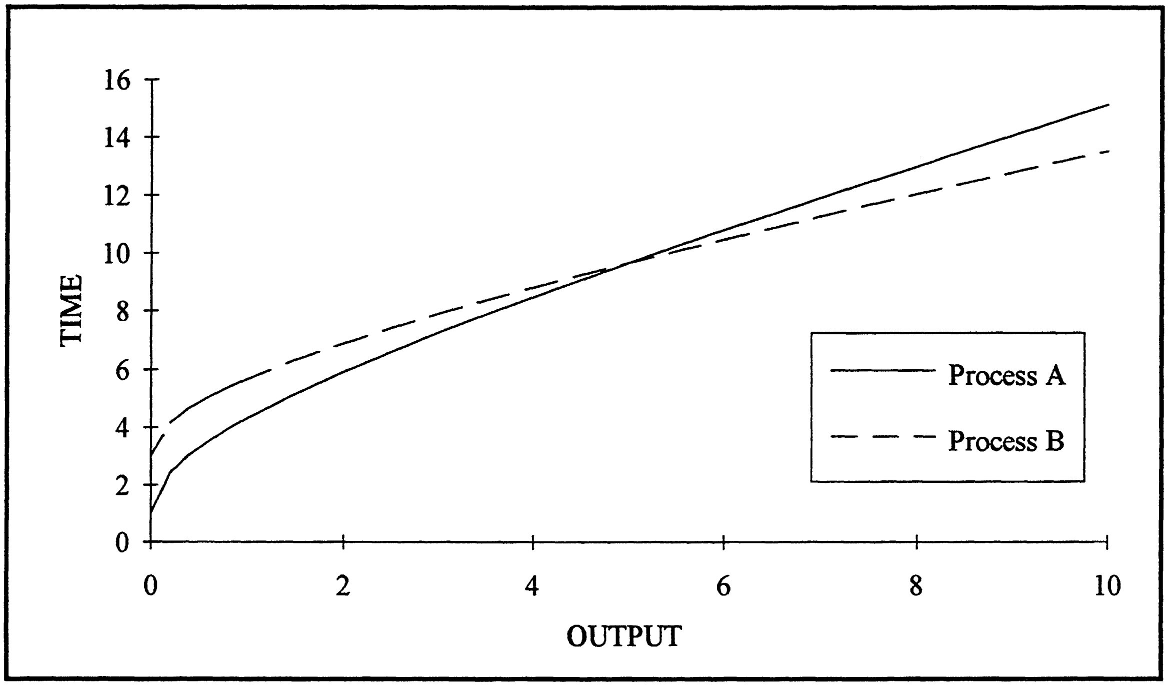


Figure 4-5. Comparison of process characteristics.

There are fundamental differences between scatter associated with time predictions for human controlled and machine controlled processes. A far greater scatter normally exists for human controlled processes. In the future, the ability to predict not only the nominal or average time but also a measure of the expected ranges (i.e. standard deviation) associated with each process step would be beneficial.

4.4.2 Manufacturing Time - Resource Cost Relationships

Each process step may consume a different mix and amount of resources. The resources can include labor, capital, facilities, materials and others and are generally unique to each process step.

All manufacturing time, resource cost relationships used on the program are based on the ACT cost ground rules shown in Table 4-1. Although capital costs are not directly assessed, recurring and non recurring wrap rates imply a burden factor which indirectly accounts for some capital costs. These cost ground rules for recurring and non-recurring labor, which infer a smeared burden, do not give the visibility of (or allocate appropriately) the actual cost of all resources consumed. For example a worker hand laying prepreg tape on a simple table would not incur the same costs per hour as a worker operating a multi-million dollar automated fiber placement machine. The present ACT ground rules would not differentiate the required skills or burdens for the capital costs of a simple table versus the AFP machine on an hourly basis. To fully address the issue of designing cost effective structures, whether metal or composite, all resources utilized must be appropriately allocated. Future studies plan to consider a more rigorous assessment of the capital costs for specific concepts.

<u>ACT Ground Rules for Recurring Costs</u>: 1. Production is based on a total of 300 shipsets at a rate of 5 shipsets per month. 2. Labor is estimated at the detail process level. 3. Machine times are based on performance data provided in the automation plan. 4. Material is based on total area or volume required to produce a part, including an appropriate process-based utilization rate. 5. All costs are based on 1995 dollars. 6. Recurring labor wrap rate is assumed to be $100/hr.
<u>ACT Ground Rules for Non Recurring Costs</u>: 1. Rate tooling is included to support a monthly rate of 5 shipsets. 2. The estimate assumes that all innovative ideas created for technology of 1995 will be obtainable. 3. The estimate assumes a dedicated facility and equipment to minimize factory flow and hand labor. 4. Capital equipment and facilities costs are not included as a separate item. 5. Non recurring labor wrap rate is assumed to be $75/hr.
<u>General Approach Used By ATCAS</u>: Cost assessments used detail design and manufacturing definitions, and continuous discussions between the DBT and cost estimating group. An automated factory was assumed for definition of equipment and tooling. Focus was on (1) efficient processes, (2) the reduction of part count and handling steps, (3) low cost composite materials, and (4) the combination of manufacturing operations where beneficial.

Table 4-1. ACT cost ground rules.

Internal policies and practices will lead to differing manufacturing time - resource cost relationships being used in different companies. Boeing's costs will not be the same as other manufacturers. This type of cost information is generally highly protected. For this reason the ACT ground rules were established to maintain consistency between all ACT contractors. When used internally, the actual company manufacturing time - resource cost relationships can be used.

Treatment of Non-Recurring Costs.

Great care must be used in determining the manufacturing time - resource cost relationships to be used with a designer's cost model especially for non-recurring costs.

If the production scenarios and investment strategy are known then non-recurring costs can simply be allocated equally on each ship set produced. Often the production scenarios and investment strategy are not known or non-recurring costs are shared between differing products. In this case some non-recurring resource costs such as capital equipment, facilities and non-recurring tooling can be accommodated (or allocated) by calculating a cost on a time of use basis. That is, capital costs for an autoclave can be calculated on an hourly basis based on the purchased price of the autoclave, interest rates, use factors, durability, scrap recovery costs etc. Great care must be used when employing this technique. If capital equipment exists and excess production capabilities are available, one can argue that capital cost should *not* be included in a designer's cost model. Once non-recurring costs are incurred, designers can only minimize costs by utilizing the available capacity that exists. Therefore designers may ignore capital costs for processes that are available and capacity exists for. Ask the question "what will the costs be if a particular process is *not* used?"

Factory flow can also influence the manufacturing time - resource cost relationships. The desired production rate will influence the number of identical tools and capital equipment required. If non-integer numbers of capital equipment are required (e.g. 1.1 autoclaves) then difficulties arise. If only one autoclave was purchased the production rate could not be met. If two were purchased then on average, one autoclave may be idle for 90% of the time causing much higher capital costs. Early in the concept development effort, non-integer values for the number of capital equipment items may be adequate. However as the design is refined and production approaches, integer numbers are required.

4.5 Factory Equation Sets

Factory equation sets are simply the set of equations that represent the entire manufacturing plan. These sets contain the understanding of the costs associated with the manufacturing effort. Different sets can be produced, each corresponding to a differing manufacturing scenario. Designs are then tailored within each scenario and compared.

4.6 Refinement of Cost Equations

Cost equations are refined by modifying the manufacturing plans, manufacturing process step times and manufacturing time - resource cost relationships.

A more detailed understanding of a manufacturing process generally means more steps will be used to represent it. Each step would represent a smaller amount of the cost. Therefore as a design matures the number of process steps will generally increase.

Each process step equation can be refined by collecting data from time studies (for recurring cost) taken in manufacturing trials and continuing to develop the scientific understanding of those times. Manufacturing time - resource cost relationships are enhanced by a more complete understanding of factory flow issues and actual resource costs.

4.7 COSTADE Cost Algorithm

The COSTADE cost algorithm is based on a general framework which allows numerous model types to be used. The cost model equation forms and cost coefficients are contained in an input data file, allowing for model changes without recompiling COSTADE. The cost algorithm input file is analogous to a bulk data file for a structural finite element analysis program, where the model geometry, material properties and loading conditions are contained in the input file and not in the finite element analysis program. Detailed estimating procedures, parametric models, scientifically derived equations, and other models can be used in COSTADE. This allows the user to select the equations that are most appropriate for their situation, and does not tie COSTADE to one type of cost estimating procedure. The cost models used to date on the ATCAS program have typically been developed at the individual process-step level, although the cost algorithm allows for the definition of more general models.

Due to the representation of the design as discrete elements, there are issues associated with providing the appropriate design information to the cost equations. The cost equations are evaluated at the panel level (not at the element level) due to the frequent non-linear behavior of fabrication cost with size. Therefore a fundamental problem exists in how to calculate the required panel level design information from the available library of element level design information. Various summing techniques are available for this purpose. Summing over all elements, a single row, a single column or over a user defined set of elements is allowed to calculate the panel design information for each cost equation. The actual summing techniques used are specified in the cost input files. The user defined summing technique offers the most general capability at the expense of making cost input files dependent on the mesh used. If the design element mesh is altered, then any user defined summing specifications will generally need to be revised.

Reference 4 documents the COSTADE cost algorithm in more detail.

4.8 COSTADE Process Cost Analysis Database

A relational database is used to manage process step cost equations and manufacturing plans as described in Reference 5. This database can produce COSTADE cost input files or stand alone cost estimates. COSTADE design value files can be read by the relational database to update its design values. The ability to relate parts, processes and resources in this software application speeds the development of manufacturing plans and maintains consistency between cost estimates.

5.0 STRUCTURAL ANALYSIS AND LOAD REDISTRIBUTION

The COSTADE sizing modules are stress analyses required to ensure that skin/stringer and sandwich composite fuselage designs meet structural integrity requirements. These analyses include: tension and compression strength predictions with small damage for ultimate load cases, axial and hoop direction large notch residual strength for fail-safe load cases, pristine strength predictions, general panel stability (including transverse shear flexibility), local buckling of stringer elements, sandwich-specific stability modes (face wrinkling, crimping, dimpling, core crush), minimum overall axial and shear stiffness, load sharing between stiffeners and skins and Poisson's ratio mismatches. The optimization algorithms required for the global design space and discrete valued composite design variables dictate that closed form analyses must be used in order to reduce computing time. Multiple load and pressure cases are accommodated. Associated limits on the design are imposed by specifying ranges for stiffener and frame spacing and geometry, laminate ply stacking sequences and laminate and core thicknesses.

Closed form solutions, which form the basis for algorithms for cutouts and splices, have been developed. Ref. 21 presents the cutout analysis being investigated while Ref. 22 presents the splice analysis developed. At present, these routines have been used only to a limited extent.

In order to account for the possible influence of model stiffness on internal load distribution, the ability to update the element internal loads has been developed through connections to finite element analyses. Links to finite element analyses have been accomplished in two ways. COSTADE has the ability to generate the appropriate element stiffness data in several common formats (NASTRAN, ASTROS and ANSYS) for plate and beam type elements (Ref. 23 and 24). Stiffener and skin stiffnesses can be smeared into the same plate element if desired. Element internal load results can be read into COSTADE in several formats including PATRAN element results files (Ref. 25). Mappings between COSTADE design element and finite element numbers allow considerable flexibility in this bi-directional link. Ref. 26 documents the use of this link with the ATCAS internal loads model.

Linking of structural evaluations in COSTADE to a global finite element internal loads model has the potential to dramatically reduce the engineering design cycle time. Prior to the loads model linkage, it was necessary to manually reduce the loads model data and assemble design element loading files, and manually update the loads model element stiffness data. The level of effort required for these manual updates (weeks to months) effectively limits the total number of updates possible. Development of the loads model link has provided the capability to examine the load redistribution effects caused by design updates in a timely fashion. This capability facilitates the use of configuration correct load distributions earlier in the structural development effort.

Also in development is an internal finite element capability currently with one finite element for each design element. This approach eliminates the overhead associated with transferring information outside of COSTADE and initiating a general purpose finite element code. The internal finite element capability is based on a displacement formulation of plane stress quadrilateral isoparametric elements with very fast execution time. This is imperative for an iterative optimization procedure to converge within reasonable execution times. Preliminary results indicate finite element analysis after each iteration in addition to ensuring a feasible design improves convergence of the optimization process (Ref. 27). This internal finite element capability is not included at present delivered COSTADE source code.

Reference 4 documents the COSTADE structural analysis and load redistribution algorithms in more detail.

6.0 MANUFACTURING ANALYSIS AND CONSTRAINTS

Manufacturing constraints are included to ensure that the designs meet manufacturing group feasibility requirements. In COSTADE, these constraints are handled by laminate design rules, panel blending functions, a dimensional stability analysis, and a manufacturing tolerance checking algorithm.

The dimensional stability (warpage) analysis is used to predict the final shape of designs with mismatches in coefficients of expansion between skin and stiffener elements (Ref. 28). This analysis is necessary to resolve mechanical assembly issues (i.e., shimming requirements) early in the structural development. Including warpage predictions also enables credible trade studies comparing the production of higher tolerance more costly parts resulting in lower assembly costs (or vice versa).

A novel procedure has been developed to ensure that designs with finite tolerances in the design variables are accommodated (Ref. 29 and 30). COSTADE can be used to determine whether a design has acceptable manufacturing tolerances. Given a design and the acceptable tolerances on each design variable, the given design is evaluated to determine whether it is feasible (i.e. has acceptable tolerances). This is accomplished by using the optimization algorithm, to check if all the possible designs that could result when the design variables are perturbed within their manufacturing tolerances, result in designs with positive margins of safety.

The fabrication cost model which captures the manufacturing performance, and the blending algorithms which ensures manufacturing feasibility, are additional manufacturing analysis capabilities of COSTADE.

7.0 OPTIMIZATION ALGORITHMS

The optimization algorithm normally used in COSTADE is a random search global optimization method called "Improving Hit-and-Run" (IHR). The IHR algorithm enables efficient searches for global minimums for problems with large numbers of design variables (Ref. 9 and 31 through 34).

A global optimization algorithm is used because the optimum design of laminated composite structures is truly a global problem, in which the associated design space contains many local minima. A global optimum is computationally more expensive to identify than a local optimum, so the choice of an optimization technique is of critical importance. The complexity of global methods, such as a grid search, pure random search or multi start, are exponential in dimension. That is, as the number of design variables increase, the number of function evaluations necessary to solve the problem increases in an exponential fashion. The high number of design variables in the composite design problem renders these techniques impractical. The Improving Hit-and-Run global optimization algorithm, implemented in COSTADE, can be shown to be polynomial in dimension for a class of problems.

The IHR algorithm is a global optimization method, that can be applied to a large variety of functions, including non-differentiable and discontinuous functions. Initially IHR could only be used with continuous variables. However, the capability of using IHR with both integer and continuous variables was developed. This was necessary in order to be able to use design variables such as number of plies, which are integer variables, together with stiffener geometry and spacing, which are continuous variables. Fiber angles may be treated as either continuous or integer variables, that is, fiber angles may be restricted to take a set of fixed values, e.g. [0,+/-45,90].

Design variables can be specified as integer or continuous. In order to use integer variables the user must specify a rounding for each design variable. For instance, if fiber angles are only allowed to take values in [0,+/-45,90] the rounding is specified as 45°. For continuous variables, the rounding value is set to zero.

The IHR algorithm can be briefly summarized as follows: A sequence of points are generated during each iteration. Given a current point, a new point is generated by selecting a direction of movement in the design space and a distance to move in that direction. If the new point improves the objective function it becomes the next point, otherwise a new point is generated. There are currently four methods provided in COSTADE for selecting the direction of movement within the design space: the coordinate direction (CD), cyclic coordinate direction (CCD), hyper spherical direction (HD) and group hyper spherical direction (GHD) methods. When a coordinate direction (CD) movement is selected the new point is generated by randomly picking one design variable (out of all possible design variables) and then the new point is picked in the direction along the selected design variable. When the cyclic coordinate direction (CCD) is used, the design variables are picked in sequential order, one after the other and a point along that design variable is selected. If a hyper spherical direction (HD) is selected, the direction of movement is generated uniformly on a hyper sphere (all design variables are included) and the new point is generated along that direction. Group hyper spherical direction (GHD) randomly chooses a subset or group of all the available design variables but otherwise is identical to HD. The groups available are:

all design variables associated with a single skin ply in all elements

all design variables associated with a single stringer ply in all elements

all geometry associated with a stringer in a single element

all geometry associated with a frame in a single element.

Two line search options are available: complete line and reduced line. The complete line option searches the entire range of all design variables. The reduced line option searches a small user defined segment of the line. The reduced line search is typically used at the end of an optimization run, to zero in on a local optimum.

Fabrication cost, weight, cost subject to weight, or performance (i.e., margin of safety) can be used as objective functions. The minimization of cost subject to weight is especially useful, as this function (fabrication cost + constant * weight) aids in quantifying the acquisition cost and operating cost components of the structural life cycle cost. In the case of a tie, the margin of safety is maximized.

The optimization algorithm can take many iterations which requires the analysis to use as little computation time as possible.

Figure 7-1 illustrates the program flow during optimization runs.

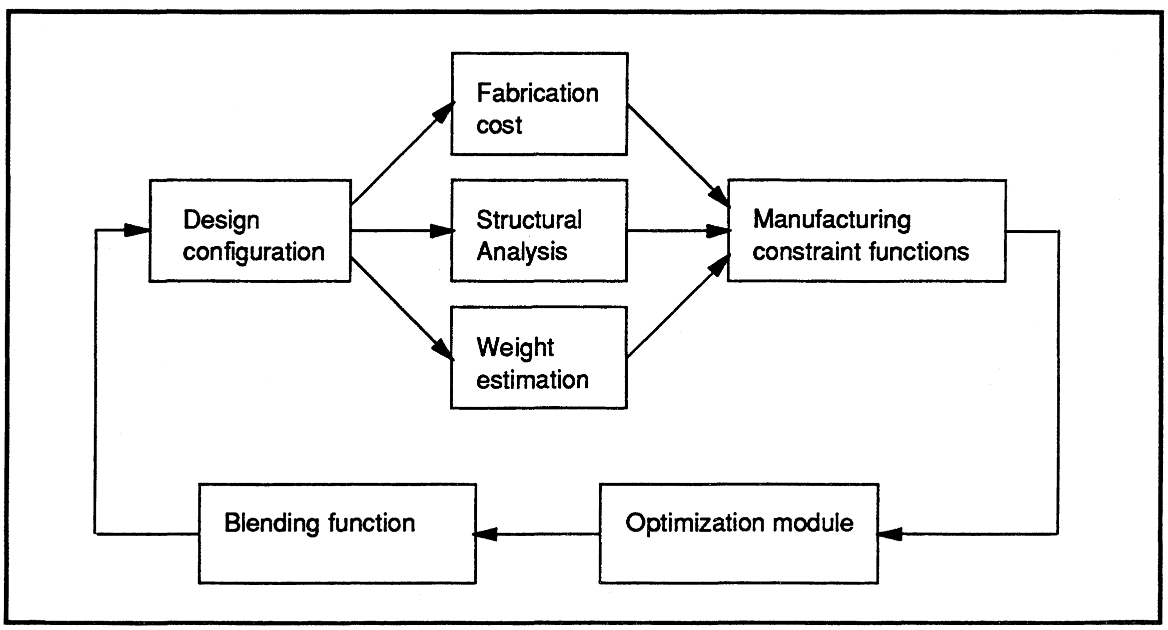


Figure 7-1. Program flow during optimization.

8.0 APPLICATION EXAMPLES

Sensitivity studies and refinement of the ATCAS crown (Ref. 11, 12 and 35), keel (Ref. 13) and initial side (Ref. 14, 15 and 36) have been performed. A summary of these studies is presented in this section. Inconsistencies between the various quadrant designs are present as these studies were performed at different times. Improvements made over time in the cost, design, manufacturing and structural analyses and the COSTADE software have resulted in these inconsistencies. Figure 2-2 illustrates the major final phase B COSTADE models developed.

8.1 Crown Sensitivity Studies

Several crown sensitivity studies for a 17.6 ft by 33.2 ft. crown quadrant were performed with COSTADE as part of the ATCAS program (Ref. 11, 12 and 35). The crown sensitivity study presented here is a summary of that documented in Ref. 12.

8.1.1 Crown Design Description

The baseline crown panel design is depicted in Figure 8-1. The stiffened skin design features cocured longitudinal hat-section stringers and cobonded J-section circumferential frames. The stringers have spacing ranging from 14 inches at the top centerline of the quadrant to 18 inches at the panel edge. The frames, spaced nominally at 21 inches, contain cutouts (referred to as mouse holes) to permit continuous stringers. The mouse holes necessitate fail-safe flanges on the frames to ensure stiffness continuity across the frame-stringer intersection. These fail-safe flanges were not included in the cost equations or structural analyses in the sensitivity studies.

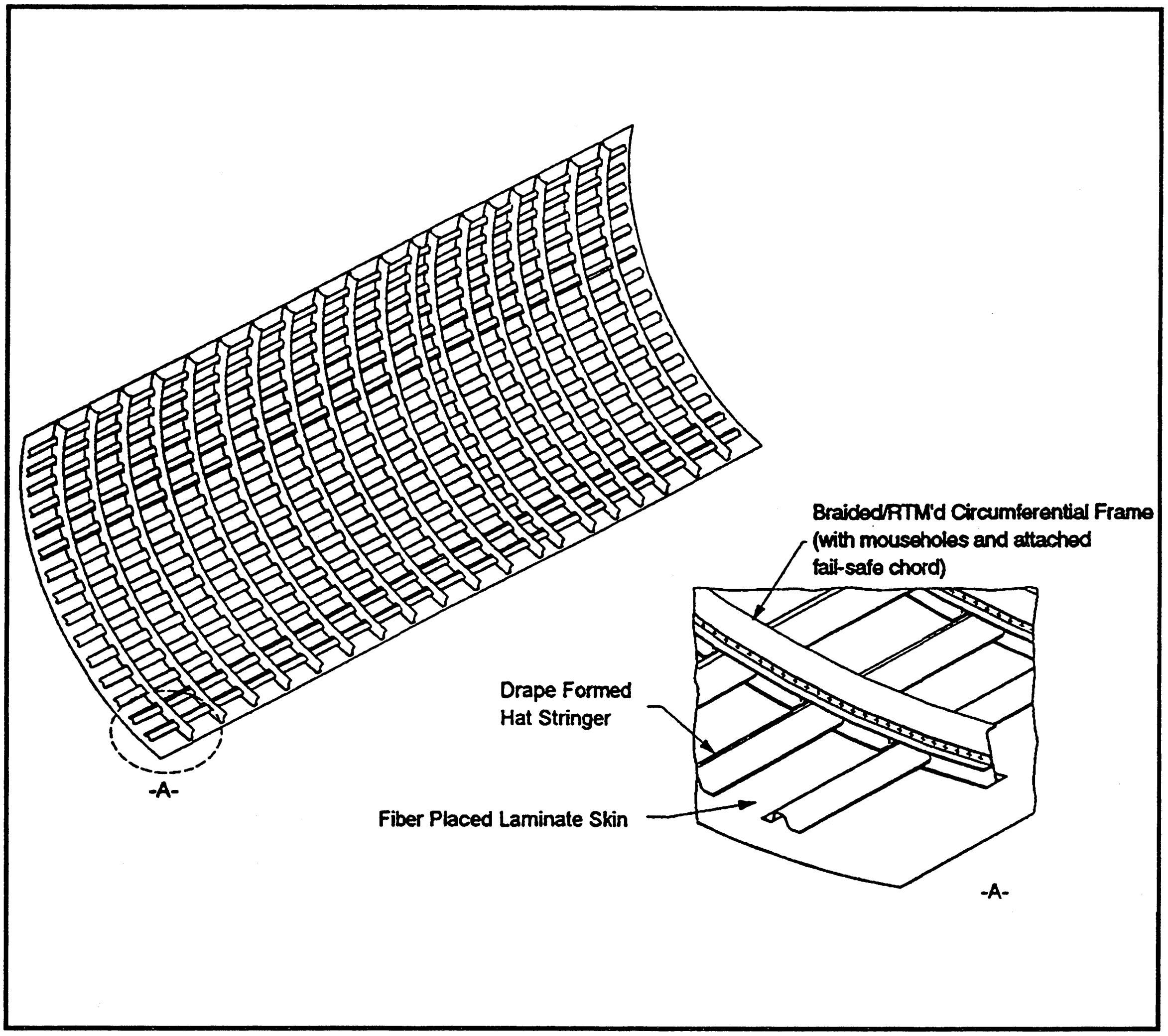


Figure 8-1. Baseline crown panel configuration.

8.1.2 Crown COSTADE Design Representation

A matrix of twelve (3 x 4) equally spaced design elements were used to model variable load conditions occurring across the crown width and length. Symmetry was assumed at the crown centerline. Three and four design elements spanned width and length dimensions, respectively, as shown in Figure 2-2.

Frame geometry was held constant in these studies, assuming a tooling constraint for less design freedom with the baseline textile/RTM batch process. Skin and stiffener design details studied in the past were allowed to vary based on automated fiber placement process capabilities and the flexible cure tooling approach adopted for the baseline skin panel.

8.1.3 Cost Equations

The Initial ATCAS Cost Equations are design/manufacturing cost relationships developed in order to optimize crown panels for cost. They were based on data collected during the crown global evaluation process, when a comprehensive manufacturing plan was compiled to support a detailed cost estimate. Individual cost drivers were determined from the detailed cost breakdown. This was accomplished by evaluating the detailed cost steps in terms of how they relate to the part definition values. By considering how each step may be affected by variables relating to the design, relationships were determined and the costs were normalized to the baseline design. Using this approach, any variance in a given design detail can be accounted for in the part cost. These Initial ATCAS Cost Equations are well documented in References 3, 11 and 35.

8.1.4 Crown Loads

Three sets each of ultimate and limit loads were used, in combination with appropriate internal pressure: maximum axial tension, maximum axial compression and maximum shear. The maximum axial tension load set, for example, was determined by identifying the load case and location within the design element that produced the maximum axial tension loads. The axial, hoop, and shear loadings associated with that load case and location were then assumed for the entire design element. The maximum axial compression and maximum shear load sets were similarly determined. In general, this method allowed loads associated with each load set to vary across the quadrant.

8.1.5 Structural Criteria and Analysis

The criteria used to design a composite fuselage crown panel are very similar to those used for its aluminum counterpart since both structures perform the same function. Many design checks were made to evaluate structural performance for each loading condition. A summary of the constraints used during local optimization are shown in Table 8-1. Using these criteria to constrain investigations to a feasible design space, structural cost and/or weight was used as an objective function in the optimization routine to find the best possible design.

Structural Criteria Related Design Checks o Ultimate strength o Residual strength (axial and hoop directions) o General panel stability o Local buckling/crippling **Structural Guidelines** o Minimum overall axial and shear stiffness no less than 90% of an aluminum counterpart stiffness o Minimum skin buckling percentage of 33% ULTIMATE load with 20% margin of safety o Maximum of 60% of the total axial load in either the skin or stringer element o Maximum stringer spacing based on skin area between adjacent stringers and frames o Minimum skin gage based on impact damage resistance data **Composite Laminate Guidelines** o Poisson ratio mismatch between skin and stringer laminate less than 0.15 o A minimum of four ±45°, two 0°, and two 90° plies in any laminate. o Ply angle increments of 15° in final laminate **Geometric, Configuration, or Manufacturing Constraints** o Maximum stringer height o Minimum stringer flange widths o Stringer web angle limitations

Table 8-1. Structural performance constraints and guidelines.

In addition to structural sizing constraints applied in previous studies (Ref. 35), a more stringent axial residual strength design goal has been adopted. This increased the axial load requirement for large penetrating damage that includes a severed stringer. The higher design goal is intended to cover a range of accidental damage threats for composite panels, providing structural residual strength consistent with that of existing fuselage.

The blending algorithms in COSTADE, allow the optimization of structural design details for large composite panels subjected to variable load conditions. For example, axial tension loads for the ATCAS crown quadrant vary from nearly 8 Kips/in to 4 Kips/in when moving forward to aft. Blending ensures that local design details such as stiffener geometry, stiffener spacing, and laminate layup are selected based on what is optimum for the full scale panel. Blending generally restricts the design space to that which is compatible with cost effective process steps. The key element used for all applicable design variables was design element 1.

Of the constraints and guidelines listed in Table 8-1, the minimum skin buckling, minimum stiffness, and tension residual strength constraints tended to be the most critical, as shown in Figure 8-2. The minimum skin buckling criteria was initially limited to be no less than 40% of the ULTIMATE compression load (i.e., skin buckling was not allowed to occur below this load level). This effectively limited the amount of post-buckling that occurred in the structure. It was later reduced to 33% of the ULTIMATE load. The minimum stiffness criteria used was based on 90% of the baseline aluminum airplane fuselage stiffness. The aluminum design is heavier in the forward end due to the higher load levels. This directly corresponds to a higher stiffness in that region. The minimum stiffness was lower in the aft crown panel where the skin gages are smaller due to the lighter loads. The stiffnesses used to constrain the composite crown designs may not be the absolute minimum fuselage stiffness allowed for this type of structure. Without extensive analysis of the effects of fuselage stiffness on aerodynamic control, ride quality, and flutter limitations, however, it was assumed to be sufficient. A longitudinally oriented through penetration that included a central failed frame element was used to evaluate hoop tension residual strength. Analytical corrections for configuration, stiffness, pressure, and curvature were included.

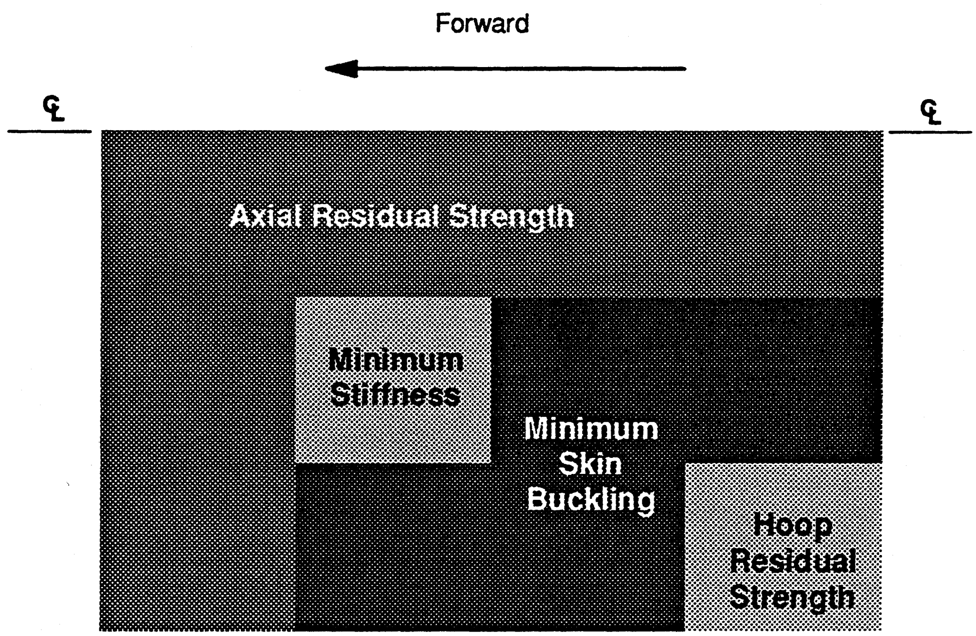


Figure 8-2. Critical margins of safety for baseline crown.

8.1.6 Crown Design Sensitivity Results

Figure 8-3 shows all cost and weight results from the sensitivity trade study, normalized relative to the point representing baseline materials (AS4/938 fiber-placed skin and stringer laminates) and design constraints. A "constant value line" representing an acceptable cost increase for weight savings was drawn in the figure to facilitate comparisons between the different concepts. Points falling above or below the line are thought to have less or more value than the baseline, respectively. Most points in Figure 8-3 fall above the constant value line. This substantiates that the baseline concept is better suited for crown panel applications than most others studied while generating the ATCAS database.

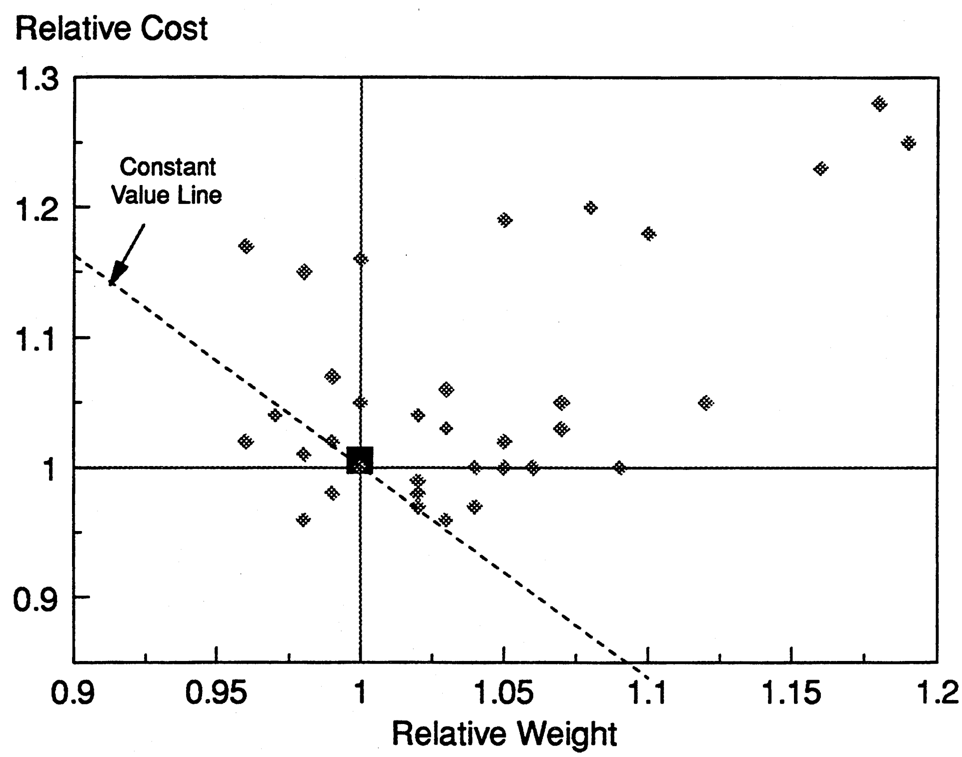


Figure 8-3. Cost and weight comparisons relative to baseline crown material and design constraints.

Figure 8-2 shows design drivers for the baseline. The current axial residual strength design goal has resulted in a small cost and weight penalty (on the order of 5%) and some changes in design detail versus those reported in earlier crown studies (e.g., Ref. 35). The optimum skin and stiffener laminate layups for the current baseline design both increased in axial modulus (by about 30%), while the average stiffener spacing dropped from 14 in. to 13 in. Other changes included an increase in the minimum skin gage from 13 to 16 plies and significant drops in the stiffener thickness when moving forward to aft. It is interesting to note that these changes to the baseline crown concept also allow a simpler mechanically fastened repair design than is possible with the softer skin and stiffener layups used previously.

Most points in Figure 8-3 were derived by optimizing for weight. One exception is the point marked "cost optimized" in Figure 8-4 which represents an analysis to minimize cost for baseline materials and design constraints. Note that this point has nearly the same value as the baseline weight optimization. The main differences between the cost and weight optimized baseline designs is a wider stiffener spacing and less stiffener thickness tailoring in the former. Differences between cost and weight optimization results for other composite crown panel designs also tended to be small. This finding may be limited to the design cost relationships for ATCAS processes (for a Family C design with cocured hat stiffeners and cobonded frames) and associated blending constraints.

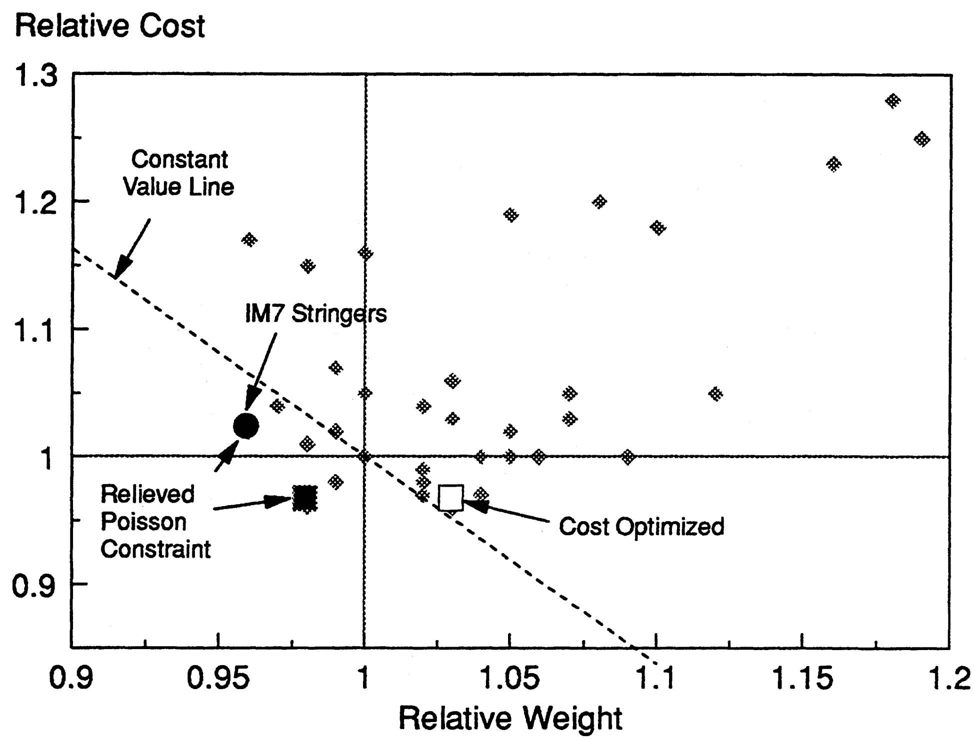


Figure 8-4. Modifications on the baseline design.

Figure 8-4 also highlights modifications to the baseline concept that give additional value to the design. The difference between skin and stringer longitudinal ($\Delta \nu_{xy}$) and transverse ($\Delta \nu_{yx}$) Poisson ratios were constrained to be within ±0.15 as a baseline design guideline. This guideline was initially meant to avoid skin/stringer separation failure modes. Other studies also suggested that a combination of both $\Delta \nu_{xy}$ and $\Delta \nu_{yx}$ constraints may be used as a guideline to minimize stiffened panel warpage as related to skin and stringer layup differences (Refs. 28, 35, 37 and 38). As shown in Figure 8-4, additional cost and weight savings were possible when the $\Delta \nu_{xy}$ and $\Delta \nu_{yx}$ mismatch constraints were relieved. These points are associated with designs having somewhat harder stringer and softer skin laminate layups than the baseline, providing some improvements in residual strength and skin buckling. Despite these improvements, Figure 8-5 shows that critical design drivers are nearly the same. Past ATCAS manufacturing experiences indicate that the additional cost savings associated with such a design are likely false due to panel warpage and cure tooling issues not accounted for in current design cost relationships. More rigorous analysis methods for constraining panel warpage in COSTADE design optimization have been incorporated in software enhancements since this study was performed.

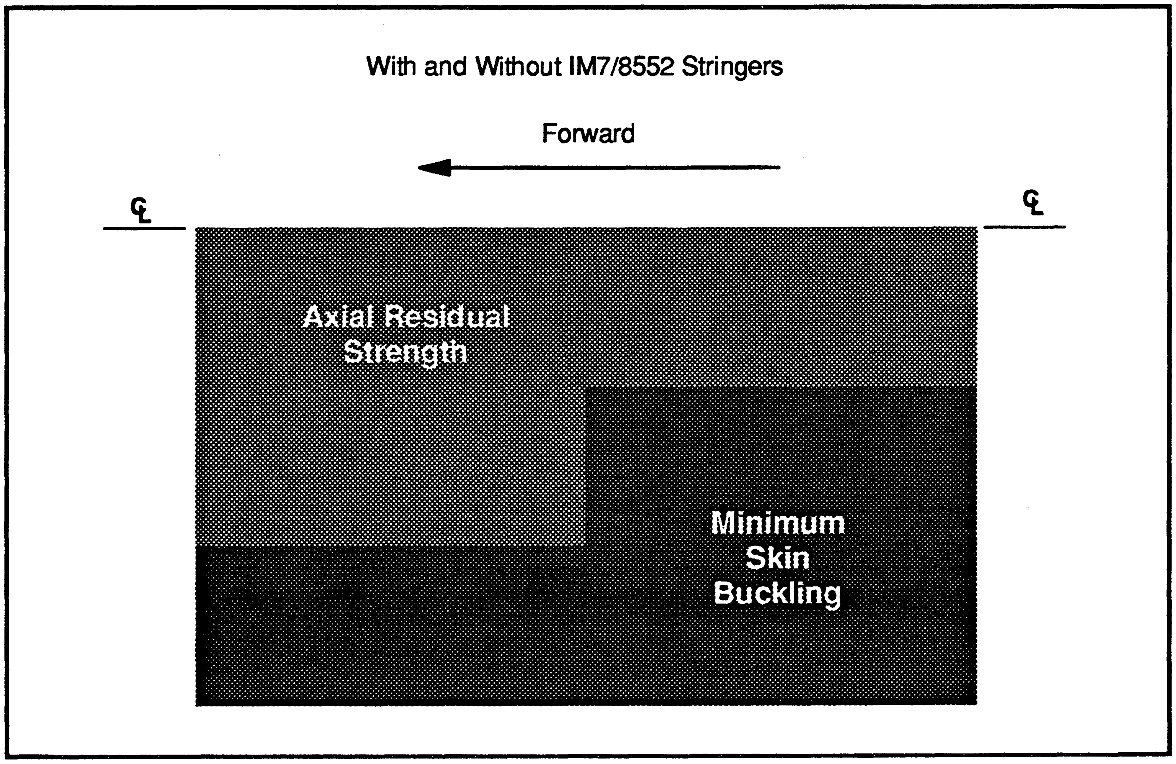


Figure 8-5. ***Critical margins of safety for the baseline design relieved of a constraint for Poisson ratio mismatch.***

One point highlighted in Figure 8-4 was derived using hat stringers consisting of IM7/938 material and relieved $\Delta\nu_{xy}$ and $\Delta\nu_{yx}$ constraints. This point appears to have value over the baseline; however, examination of other results indicated that the improvement was possible only when relieving the $\Delta\nu_{xy}$ and $\Delta\nu_{yx}$ constraints.

The cost and weight penalties associated with using AS4/938 tape for the crown skin material are highlighted in Figure 8-6. The associated design drivers are shown in Figure 8-7. The 12 % weight penalty is associated with lower skin fracture properties that have been measured for tape laminates (Ref. 12). Relief of $\Delta\nu_{xy}$ and $\Delta\nu_{yx}$ constraints results in a greater reduction in weight than observed for the baseline material (see Figure 8-4), suggesting additional benefits from relatively soft skin and hard stiffener designs when skin materials have lower fracture properties. As discussed earlier, this weight savings would have to be balanced against the increased cost risk for panel warpage. Note that the cost estimate for tape skins in Figure 8-6 assumes automated tape laminate processing with the efficiency of fiber placement. This is a reasonable assumption for automated contoured tape lamination of the crown panel skin and stringer charges. When considering hand layup processes, estimates of the relative cost for a complete crown panel increase by about 20%.

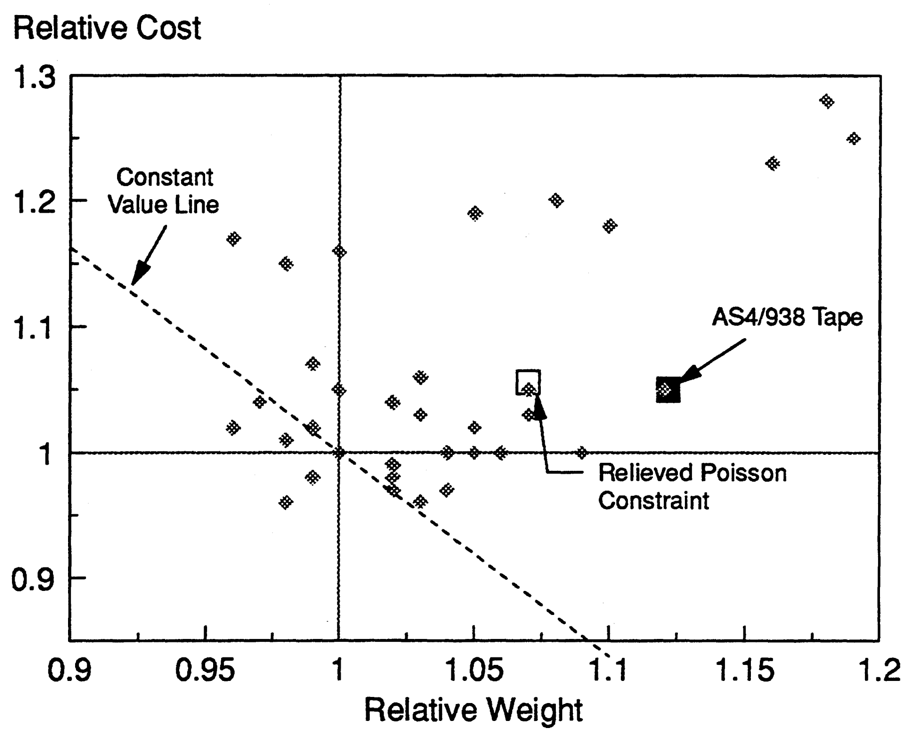


Figure 8-6. Designs using tape manufacturing process for skin.

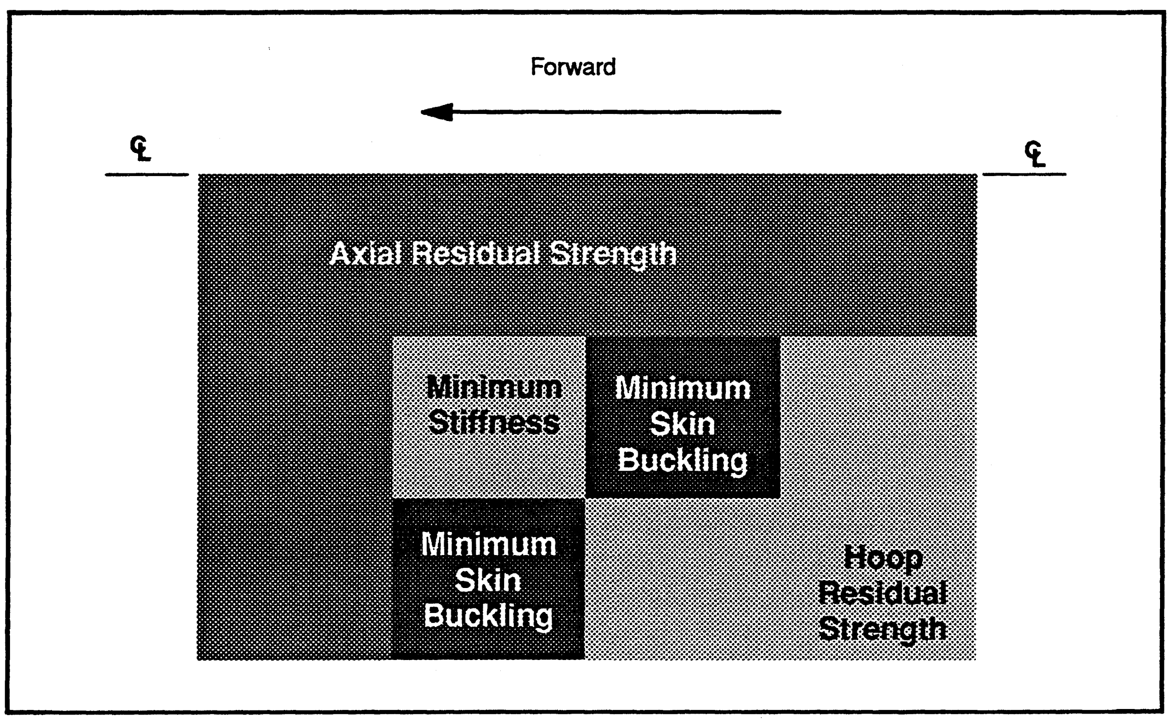


Figure 8-7. Critical margins of safety for designs using tape.

Cost/weight penalties and associated design drivers obtained when using IM7/8551-7 tape for the crown skin material are highlighted in Figures 8-8 and 8-9, respectively. Again the cost estimate for tape skins in Figure 8-8 assume automated tape laminate processing with the efficiency of fiber placement. The 18% weight and 28% cost penalties relate to much lower skin fracture properties that have been measured for IM7/8551-7 material (Refs. 39 and 40). The overall effect on the design is a closer hat stringer spacing (10 to 11 in.) and skin gages on the order of 20 plies.

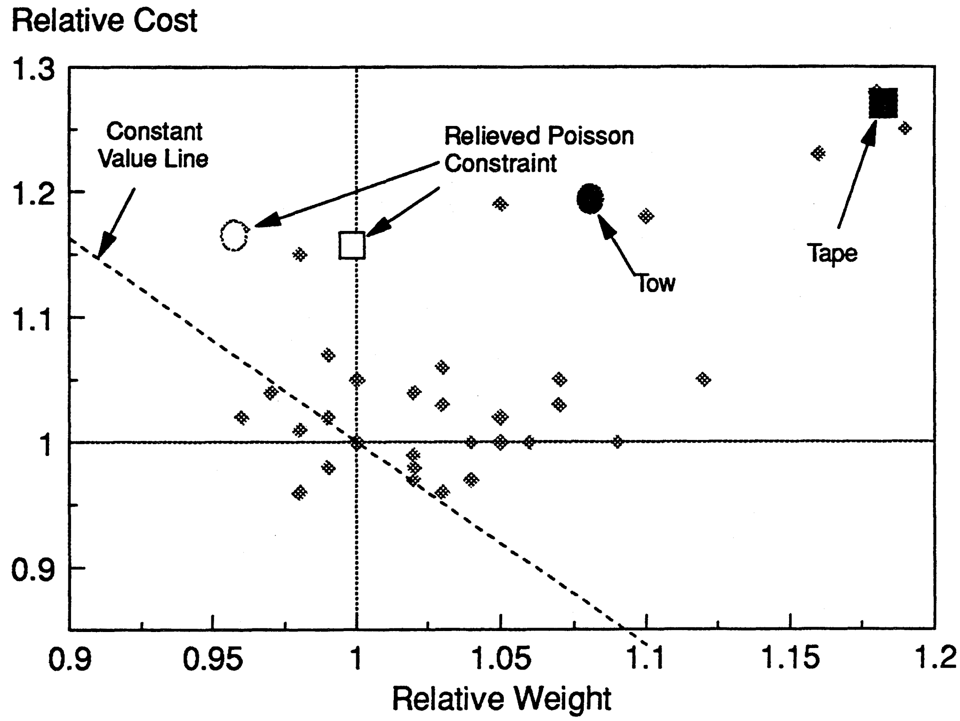


Figure 8-8. Designs using toughened matrix skin materials.

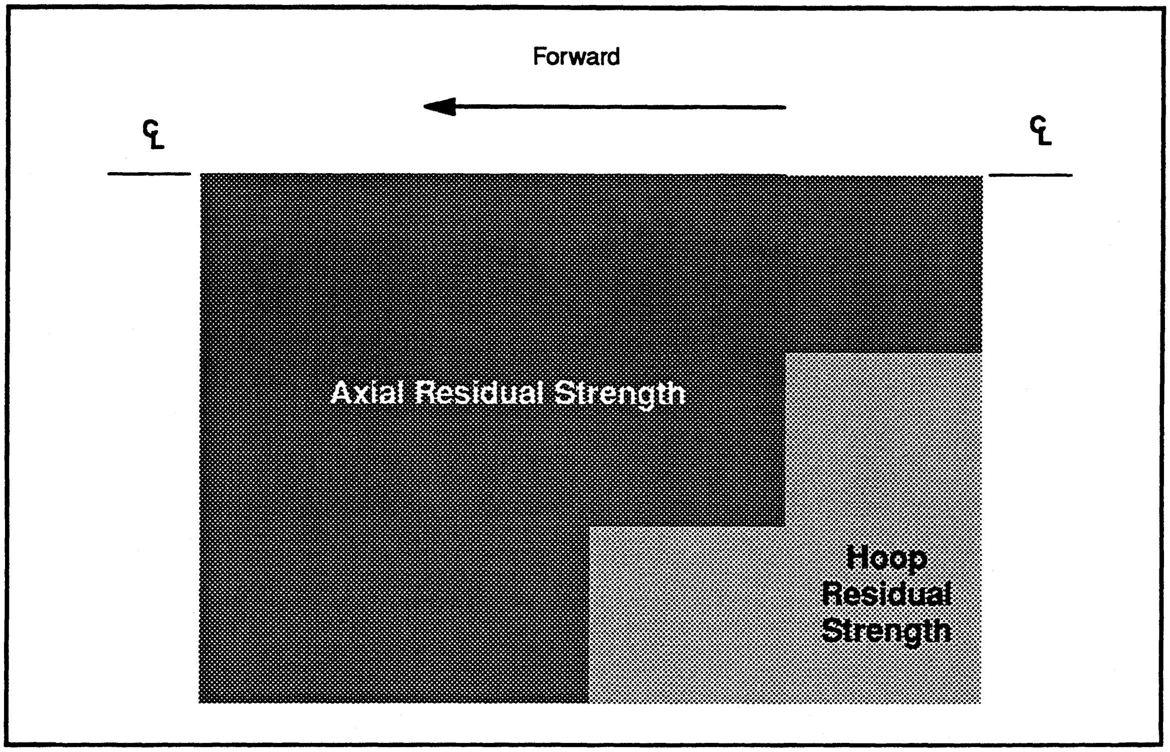


Figure 8-9. Critical margins of safety for designs using toughened matrix skin materials.

The relief of $\Delta\nu_{xy}$ and $\Delta\nu_{yx}$ constraints for IM7/8551-7 tape designs in Figure 8-8 result in a large drop in weight, approaching that predicted for the constrained baseline material. This again suggests additional benefits from relatively soft skin and hard stiffener designs when skin materials have lower fracture properties. The effect is even more pronounced than observed for AS4/938 tape because IM7/8551-7 tape laminates with soft layups have much higher fracture strains than those with hard layups. Again the risks related to panel warpage issues would have to be traded against cost benefits in order to justify relief of the $\Delta\nu_{xy}$ and $\Delta\nu_{yx}$ constraints. Figure 8-8 also estimates the possible benefits from assuming that fiber-placed IM7/8551-7 laminates would have the same relative increase in fracture properties observed between AS4/938 tape and tow.

Figure 8-10 shows typical cost and weight trades for 75%AS4/25%S2/938 hybrid skin designs. Stringers for these designs used AS4/938 fiber-placed laminates unless otherwise noted. The dark square represents a hybrid design subjected to all baseline constraints. Figure 8-11 shows that panel residual strength issues are replaced by stiffness and stability design drivers for hybrid skin concepts. This relates to the high fracture properties and reduced laminate modulus of a hybrid skin. The minimum skin buckling constraint tended to force optimum hybrid skin designs to have relatively soft layups. Some weight savings were observed for hybrid concepts when relieving minimum stiffness and $\Delta\nu_{xy}$ & $\Delta\nu_{yx}$ constraints in combination with a higher modulus stringer material. Trends shown in

Figures 8-10 and 8-11 suggest that hybrid skin materials may be more appropriate for sandwich designs that use harder laminate layups.

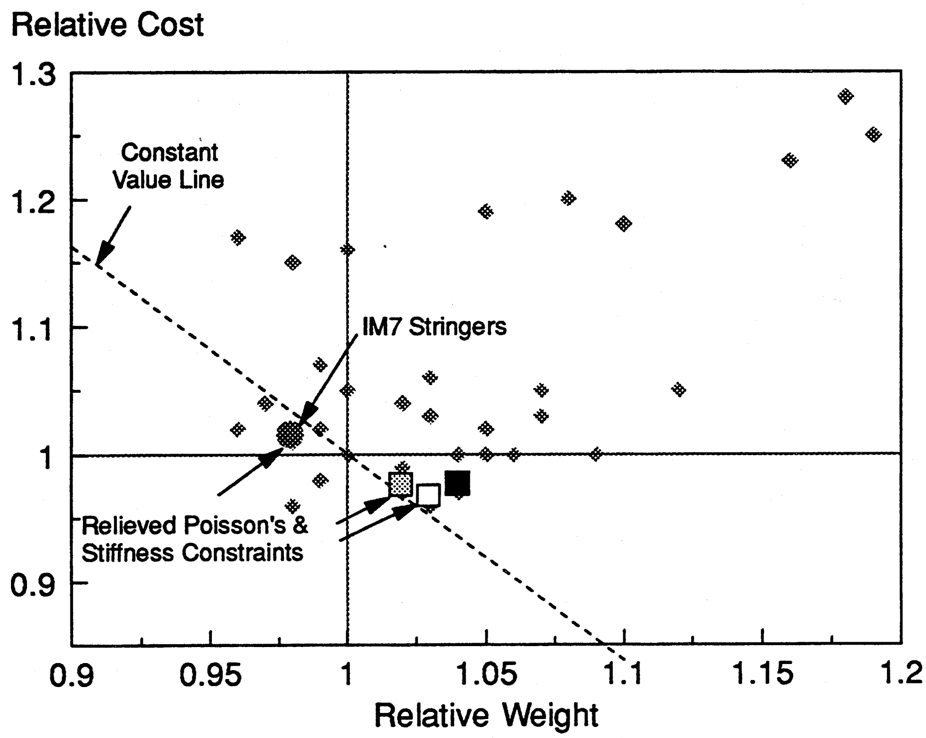


Figure 8-10. Designs using hybrid skin materials.

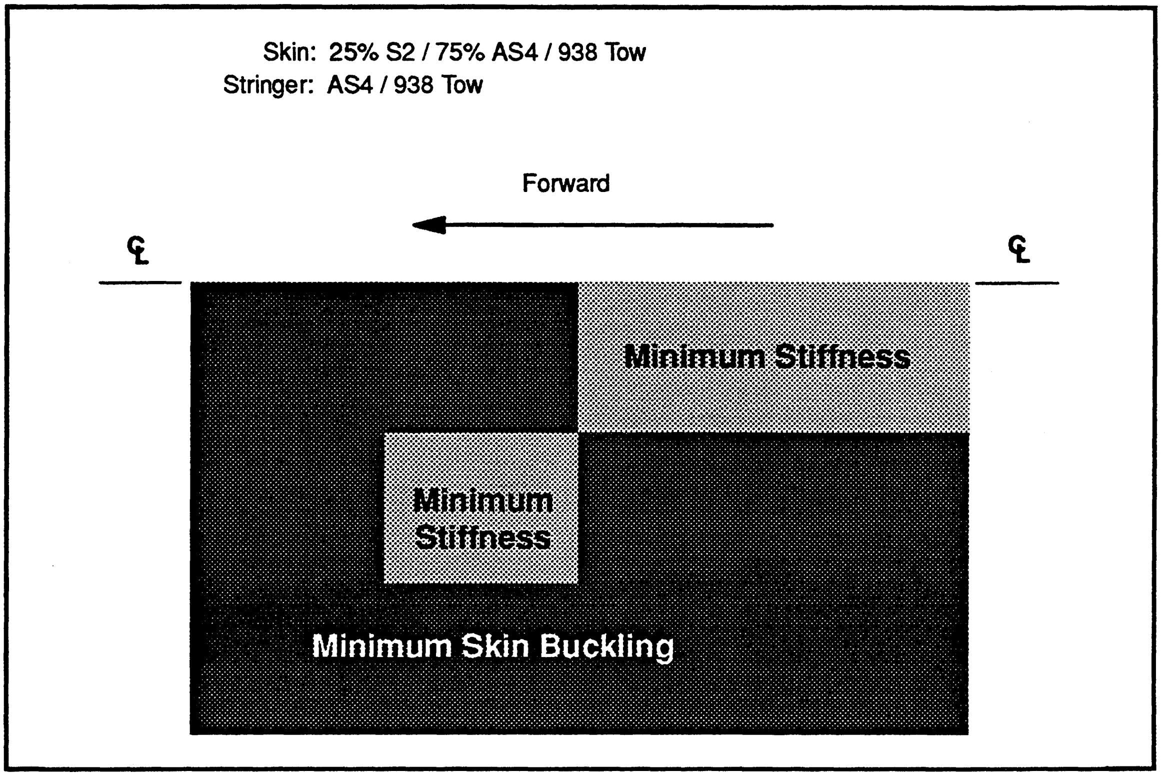


Figure 8-11. Critical margins of safety for designs using hybrid skin materials.

8.2 Keel Sensitivity Studies

The keel sensitivity study presented here is a summary of that documented in Ref. 13. More recent COSTADE keel models have been used (e.g., a more refined keel model with twice the mesh density is provided in Appendix E of Ref. 4), however this is the most complete keel sensitivity study currently available.

8.2.1 Keel Concept Description

The baseline ATCAS concept for the keel is a sandwich design with cobonded frames to provide hoop stiffening (Ref. 41) as illustrated in Figure 8-12. This design utilizes a thick laminate to carry the high compressive loads that 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 laminate is tapered out towards the aft keel, and the change in thickness is made up by an insert of core material that allows the inner radius of the panel to remain constant along its length. A constant inner radius reduces the number of unique frames that would otherwise need to be manufactured. The sandwich construction eliminates the need for stringers. The baseline materials are fiber-placed AS4/8552 facesheets, 0/90 glass/phenolic 12 lb./ft^3 core (HRP-3/16-12), 2-D braided RTM AS4/1895 frames. Core density used in this study is 12 lb./ft^3 for the entire keel, however more recent designs use 12 lb./ft^3 core in the forward keel and 8 lb./ft^3 core in the aft keel.

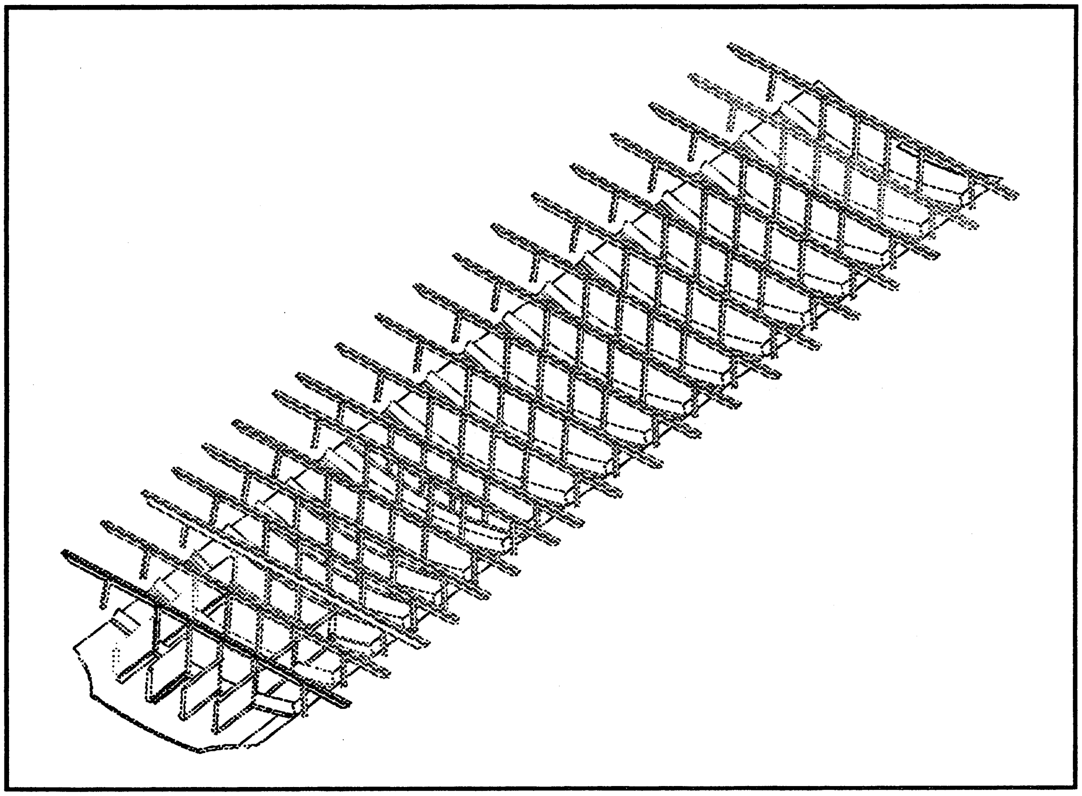


Figure 8-12. Sandwich keel assembly.

One of the critical load cases for the keel panel is a flight maneuver that causes body bending and puts the keel in compression. Typical aluminum designs carry this compression load, at the forward end, in discrete massive keel beams, or chords, which are mechanically attached to the stiffened keel skin. This concentrated load is transferred rapidly from the keel beams into the stiffened skin and then sheared out into the rest of the panel.

8.2.2 Baseline COSTADE Model of Keel Concept

The objective of the baseline COSTADE model of the keel is to allow sensitivities of the keel design to be determined and to enable optimization to be performed. The design variables considered were the panel facesheet laminates and core combination. The frame design and spacing, and therefore the floor beam design, and edge band treatment were held fixed.

In order to facilitate modeling the non-uniform nature of the keel, a forty design element discretization was implemented as shown in Figure 8-13. The designs are held fixed within each element (i.e., laminate ply stacks, core thickness, frame spacing does not change within the design element). Any variations in the designs are modeled to occur at the design element boundaries. Smaller mesh sizes therefore will refine the model in a similar manner to structural finite element analysis models.

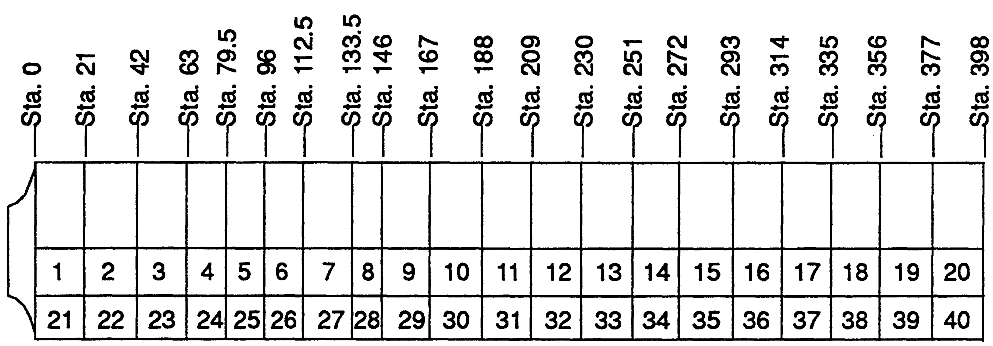


Figure 8-13. Keel COSTADE design elements.

The preliminary keel cost model consisted of equations for 88 steps representing recurring labor, recurring material and non-recurring costs associated with the major steps in the keel manufacturing process. Costs are calculated for an entire keel panel assembly. As the frame design and spacings are held constant, only the facesheet layups, core thickness and location are modified in the optimization process. Special attention was given to the skin fiber placement, core fabrication and panel bond assembly processes. These cost equations relate the part definition values with fabrication costs in an assumed fixed factory. Detailed cost estimates for the sandwich keel concept were used as the basis for developing these preliminary equations.

The facesheet laminates were limited to integer numbers of 0, 45, -45 and 90 degree plies arranged in a symmetric, balanced (in aircraft coordinates) manner. At least 10% of the fibers were required in each of the four principal material directions. The keel panel was restricted to be symmetric through the thickness and thus each facesheet was identical. To accommodate the splice requirements at the forward keel, no core was allowed in design element 1 (i.e., centerline keel station 0). All design elements were constrained to have the same overall thickness so that all frames have the same radii. This thickness constraint has a considerable influence on the frame costs. All manufacturing time, resource cost relationships used were based on the ACT cost ground rules.

Four load cases have been used in COSTADE to size the keel structure. They correspond to the maximum axial tension, maximum axial compression, maximum shear and minimum shear loading conditions as predicted from an aluminum baseline finite element loads model as shown in Figures 8-14 through 8-16. Pressure loads for each condition are accommodated as necessary. Structural analysis includes tension and compression strength predictions for the ultimate load case with small damage, axial and hoop direction large notch residual strength for the limit load case, general panel stability (including transverse shear flexibility), sandwich-specific stability modes (face wrinkling, crimping, dimpling).

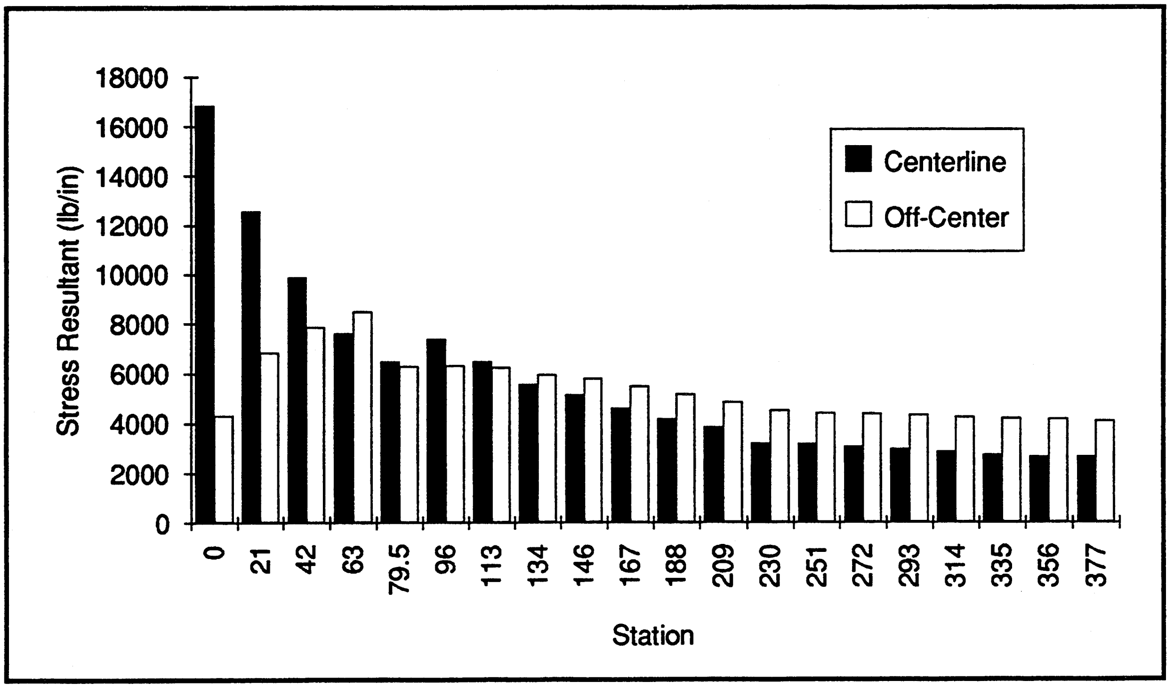


Figure 8-14. Panel loading Nx tension.

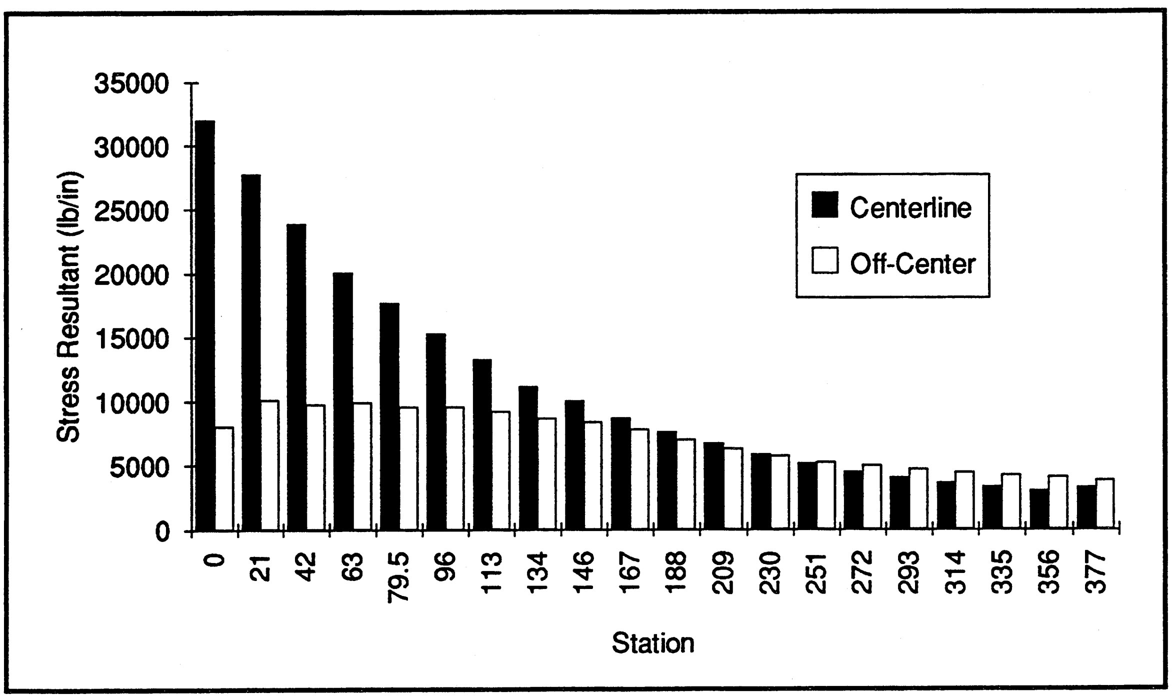


Figure 8-15. Panel loading Nx compression.

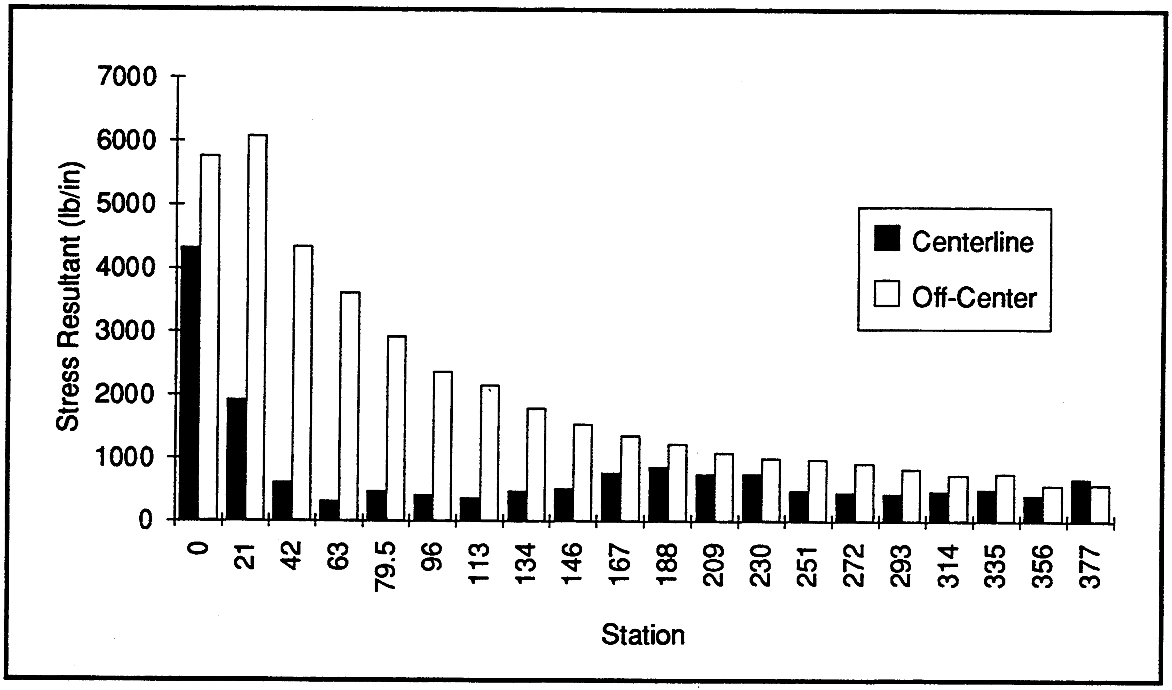


Figure 8-16. Panel loading Nxy shear.

The panel design is constrained to be manufacturable (i.e., blended) by constraining the ply angles and thicknesses of plies in adjoining design elements to be compatible. For example, if ply 1 of design element 1 has a non-zero thickness and angle θ, then ply 1 of design element 2 must also have an angle θ if its thickness is non zero. The key element used for all applicable design variables was design element 1.

8.2.3 Keel COSTADE Baseline Analysis Results

The COSTADE model of the keel presented above was optimized separately for cost and for weight. Unlike the crown post-buckled skin stringer designs, the minimum cost and minimum weight of this keel sandwich design are identical and are shown as the baseline value in Figure 8-17.

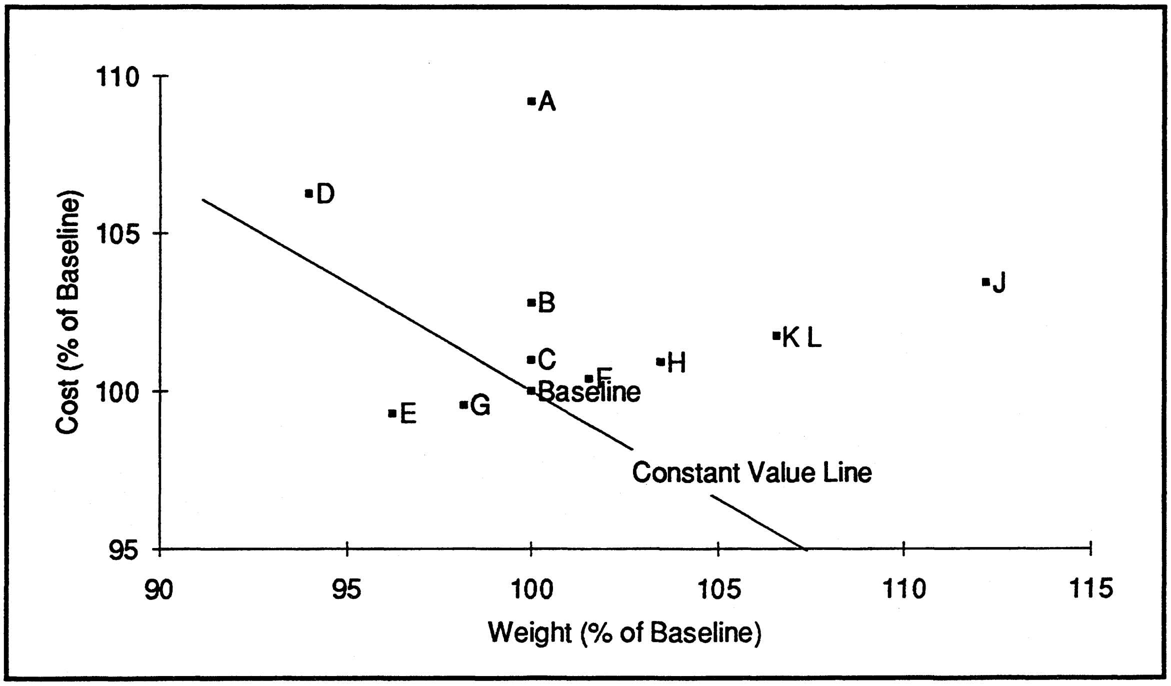


Figure 8-17. Keel design sensitivities.

The COSTADE baseline keel fabrication cost components are shown in Figure 8-18. Only the skin fiber placement and core fabrication processes are affected by design parameters which were allowed to vary in the optimization procedure outlined above, since the frame design and spacing were fixed. The breakdown of recurring labor, recurring material and non-recurring costs is shown in Figure 8-19.

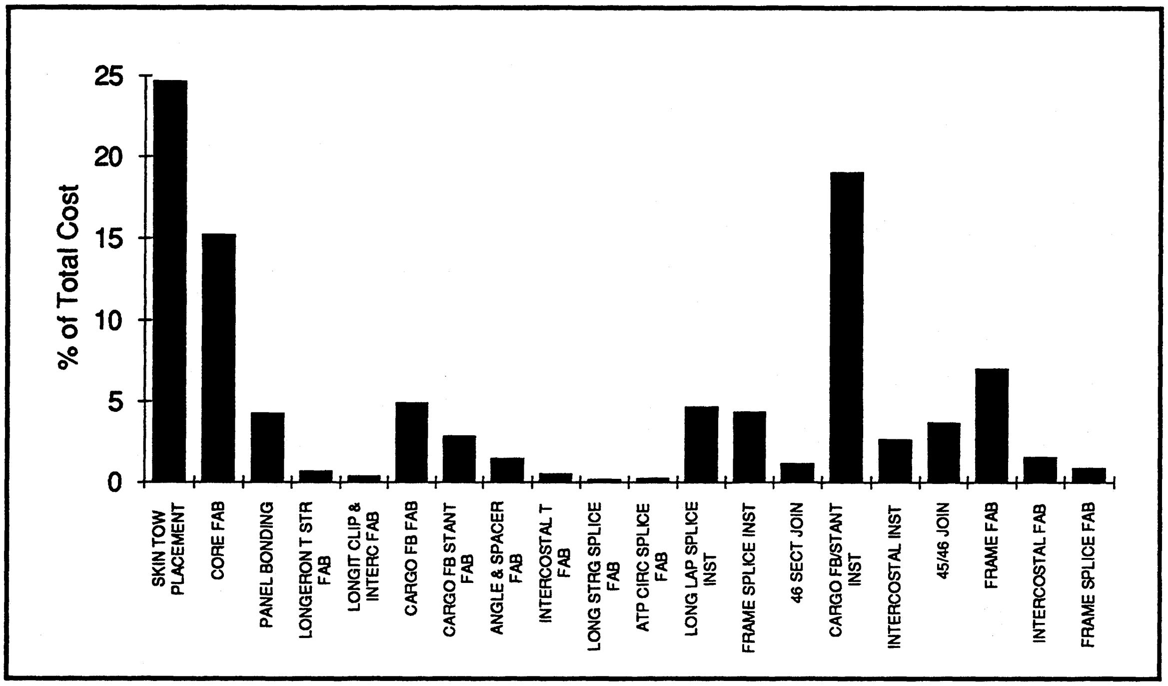


Figure 8-18. Baseline keel cost centers.

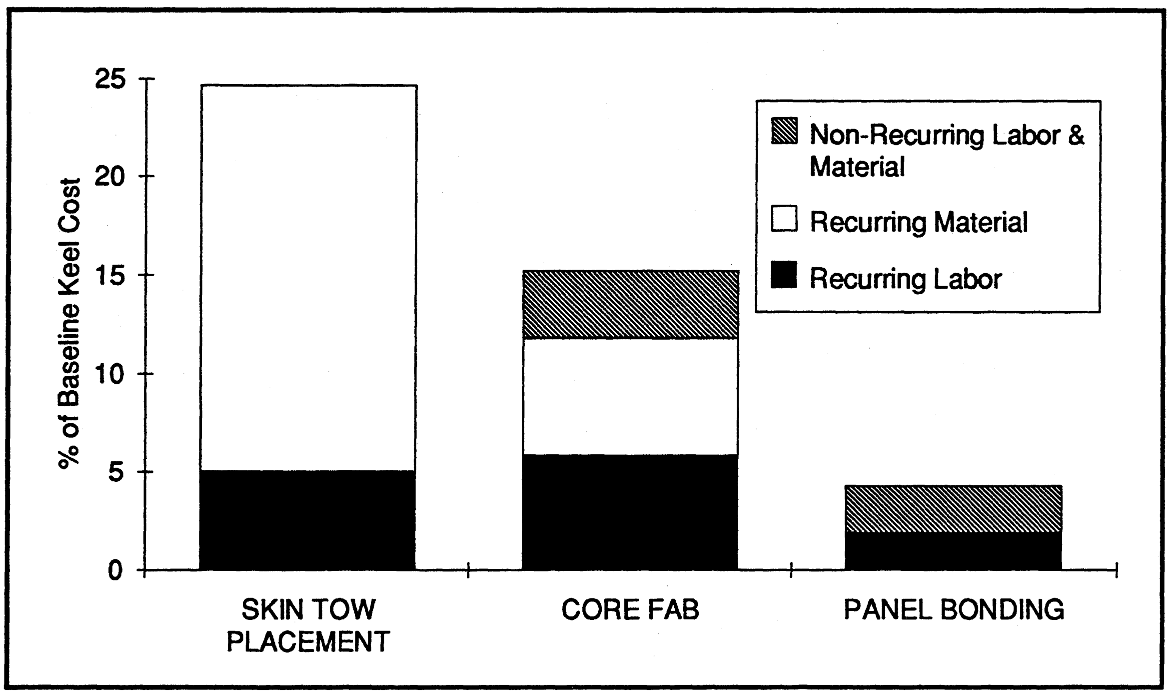


Figure 8-19. Cost breakdown for baseline keel.

The overall thickness of the panel is governed by shell buckling in design element 2 (i.e., station 21). The facesheet thicknesses (Figure 8-20) over much of the panel are governed by ultimate load case compression (small notch, barely visible damage) strength. Residual axial compression (large notch) condition may become critical if the strength assumed here (i.e., 2500 micro strain) cannot be met. The residual axial tension (large notch) strength produces the lowest margin of safety in a small area of the aft keel (i.e., off-center station 293), however it is not a major design driver. The blending requirements and minimum percentage of plies in each fiber direction affect the design in a number of elements. The minimum margins of safety are shown in Figure 8-21. Those design elements with high margins of safety are governed by a combination of the blending constraints, the required minimum percentage of plies in each fiber direction, and the balanced/symmetric/ identical facesheet constraint. The high margins in the keel aft center area indicate that a local padup for the aft keel off-center area may be warranted.

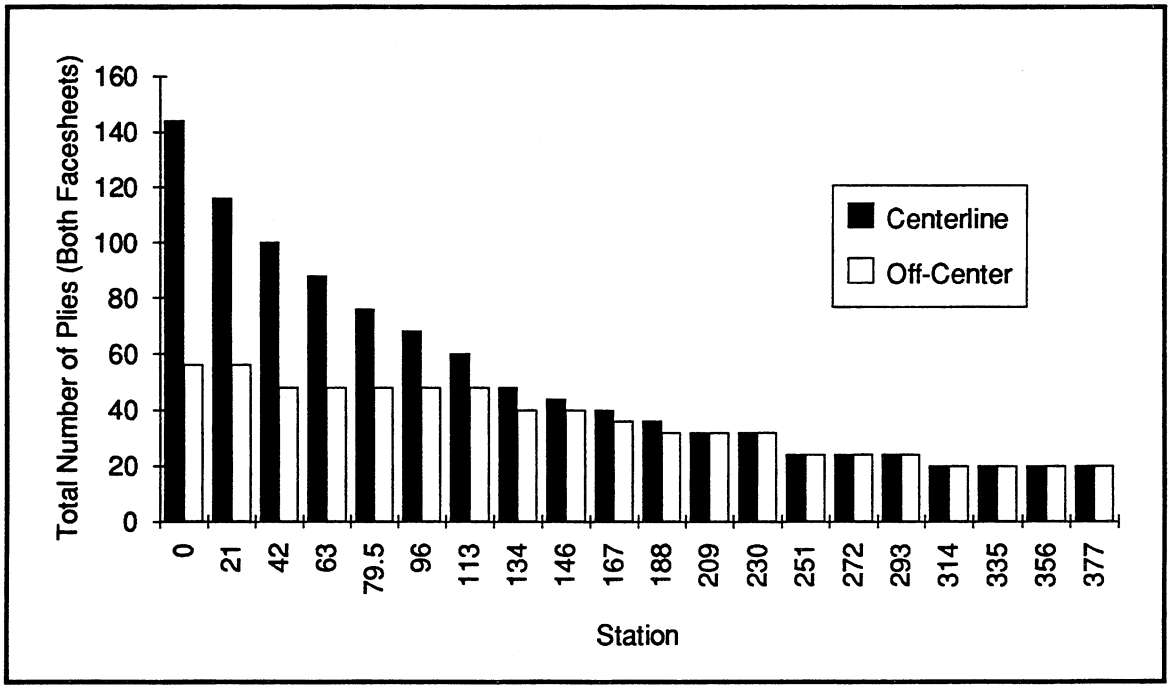


Figure 8-20. Total number of facesheet plies.

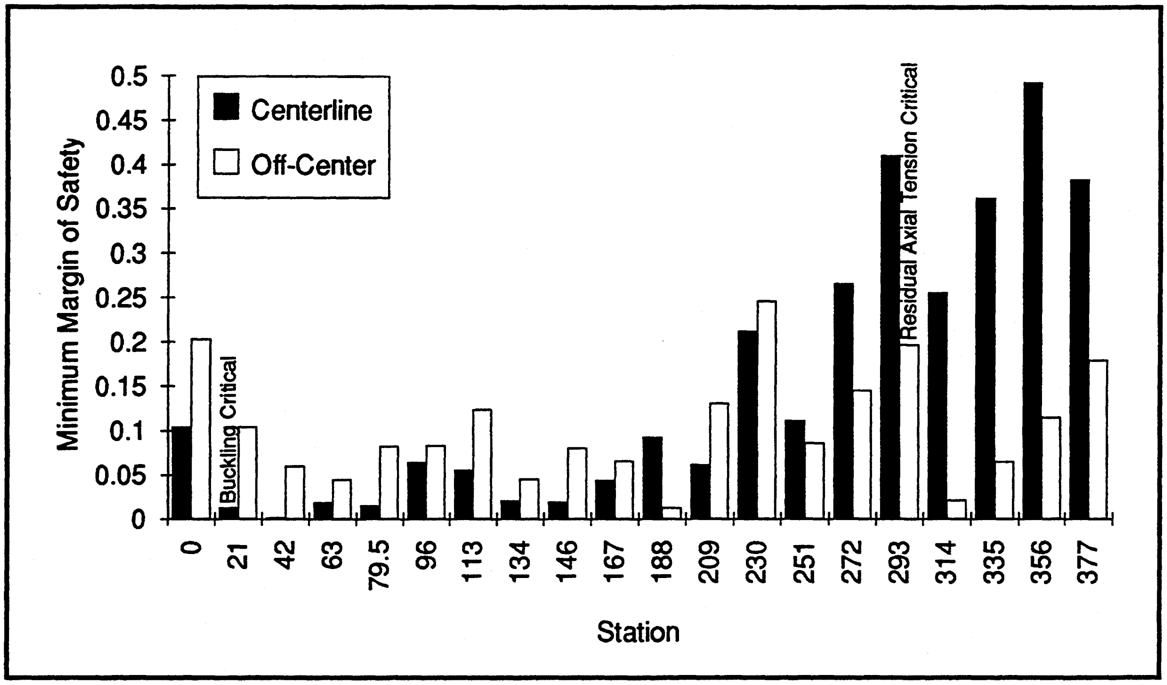


Figure 8-21. Minimum margin of safety.

8.2.4 Keel COSTADE Sensitivities

Sensitivities of the baseline COSTADE keel design were investigated by considering the effects of various cost, material, manufacturing, and structural changes on the design as shown in Figure 8-17. The constant value slope of $100/lb. is shown for reference purposes.

Fifty percent increases in the costs of AS4/8552 facesheet material, core material and AFP (automated fiber placement) facesheet layup time result in overall keel cost increases of 9.2, 2.8 and 1.0 percent, and can be related to the baseline costs shown as points A, B and C in Figure 8-17. This indicates the importance of a reliable facesheet material cost value. The AFP speed and other AFP parameters could become important if the production rate was such that additional tooling and equipment were required to accomplish the rate.

Sensitivities of a facesheet material change to IM6/8552 or a core material change to 8 lb./ft^3 are also shown as points D and E in Figure 8-17. Note that both the overall cost and weight of these designs change as COSTADE modifies the design to suit the change in material performance. The reduced weight of the IM6/8552 design does not justify its additional cost.

Including manufacturing tolerances for ply angles in the design results in a 0.4% cost increase with a 1.6% weight increase as shown as point F in Figure 8-17. The manufacturing tolerance "design" includes the requirement that the design is feasible with ply angles ranging within plus or minus two degrees of the nominal values.

Structural feasibility sensitivities were investigated by considering variations in the symmetric/balanced/identical facesheet requirement, minimum stiffness, ultimate load strength and residual load strength values.

Replacing the symmetric/balanced/identical facesheet requirement with a symmetric/balanced requirement for the sandwich overall results in a 0.4% cost reduction with a 1.8% weight reduction (point G in Figure 8-17). The manufacturing plan may not allow this change due to warpage issues if facesheets are cured at different times.

The baseline design has significantly lower shear stiffness in some areas than an equivalent metal design. The result of enforcing the design to have at least 90% of the metal design shear stiffness is a 0.9% cost increase with a 3.5% weight increase (point H in Figure 8-17).

Due to concern for the reliability of the laminate strength properties and associated methodologies, sensitivities to the ultimate and residual strength were investigated. Point J in Figure 8-17 shows that reducing the ultimate load strength by 10% results in a 3.4% cost increase with a 12.2% weight increase (the baseline design can tolerate a 0.13% reduction in ultimate load case strength without required change). Point K in Figure 8-17 shows that reducing the residual load strength by 20% results in a 1.7% cost increase with a 6.6% weight increase (the baseline design can tolerate a 9.2% reduction in residual load case strength without required change). These results indicate that the baseline design has far greater sensitivity to the ultimate load strength than the residual load strength. More recently obtained strength data indicates that residual strength plays a far more important role in the design than indicated in this study.

A practical matter of importance is the design sensitivity to load increases. An increase in loading of 10% results in a 1.8% cost increase with a 6.6% weight increase as shown by point L in Figure 8-17. This design for increased load was constrained to have the same overall thickness so that the frame radii are not affected. The added capability of this design is a result of trading core thickness for laminate thickness while keeping the overall thickness of the panel constant.

8.3 Side Sensitivity Studies

The side sensitivity study presented here is a summary of that documented in Ref. 14. More recent COSTADE side models have been used (e.g., a more refined side model is provided in Appendix E of Ref. 4), however this is the most complete side sensitivity study currently available.

Initial side panel sensitivity studies were intended to exercise the AFP cost algorithm, investigate the performance of the multiple key element blending algorithm, and ensure that the cost, manufacturing and analysis database, developed during global evaluation, had been successfully captured in COSTADE. A feature of COSTADE is the ability to cover a wide range of design scenarios, from the preliminary design phases of a program where significant design changes are allowed (and the design space is relatively unconstrained), to the detailed design phases where local details are defined (and the design space is highly constrained).

8.3.1 COSTADE Side Panel Structural Representation

The initial COSTADE representation of the ATCAS side panel used 25 design elements. The element configuration, shown in Figure 8-22, is based on panel geometry (door and window cutouts) and predicted load gradients. Design elements in COSTADE are constant geometry elements, with all ply drops occurring at element boundaries.

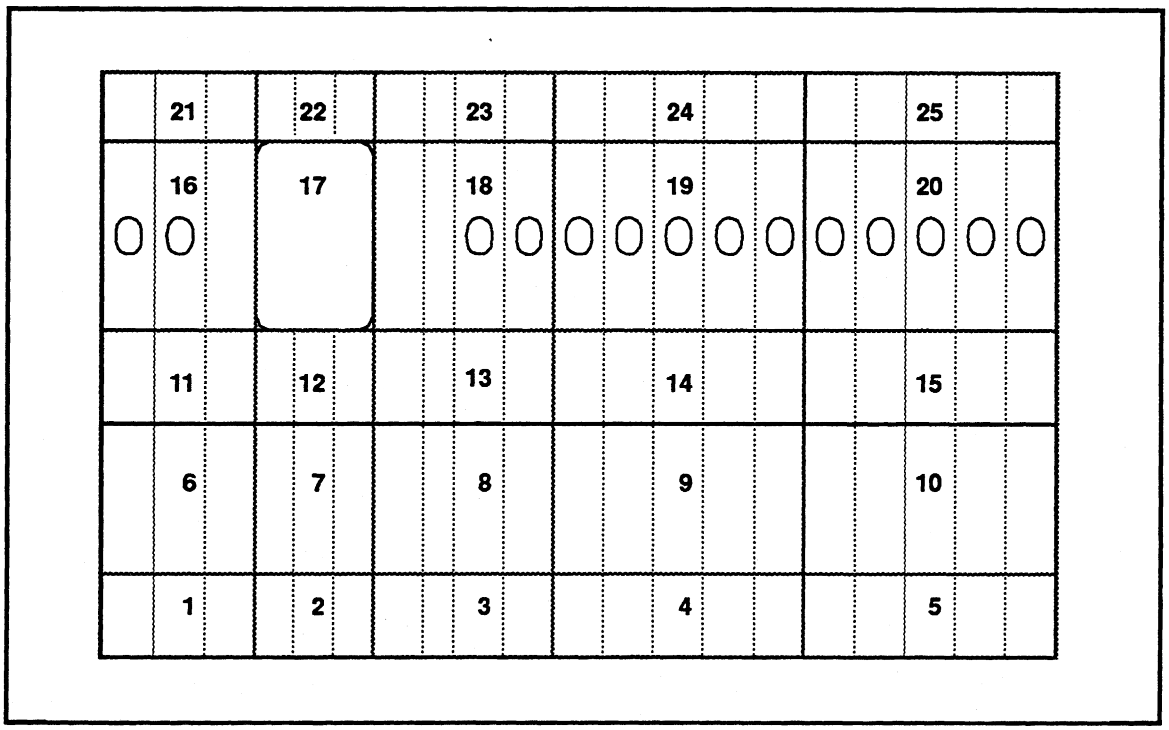


Figure 8-22. COSTADE side panel representation.

The mesh density in Figure 8-22 is selected to satisfactorily simulate actual ply adds and drops away from cutouts. The door and window cutouts present complications in the side panel application that were not present in previous applications to crown and keel panels. The door cutout is represented by an element with no loading, and the design elements in the window belt region use standard elements.

Critical skin panel loads result from flight maneuvers as depicted pictorially in Figure 8-23. Three load cases are considered in the side panel analysis. In general, maximum shear loads result from pitch maneuvers while maximum axial tension and compression loads are induced by yaw maneuvers such as rudder or engine out conditions. Furthermore, the aircraft configuration subjects the side quadrant to locally intensified load levels in several areas. As can be seen from the contour plot of maximum axial load (Figure 8-24) resulting from various flight conditions, the wheel well creates a load shadow in the lower forward area, with load intensity increasing as load is sheared in from the keel. Also, the passenger door cutout causes severe local load concentrations. Similar trends are observed for the maximum shear loads (Figure 8-25).

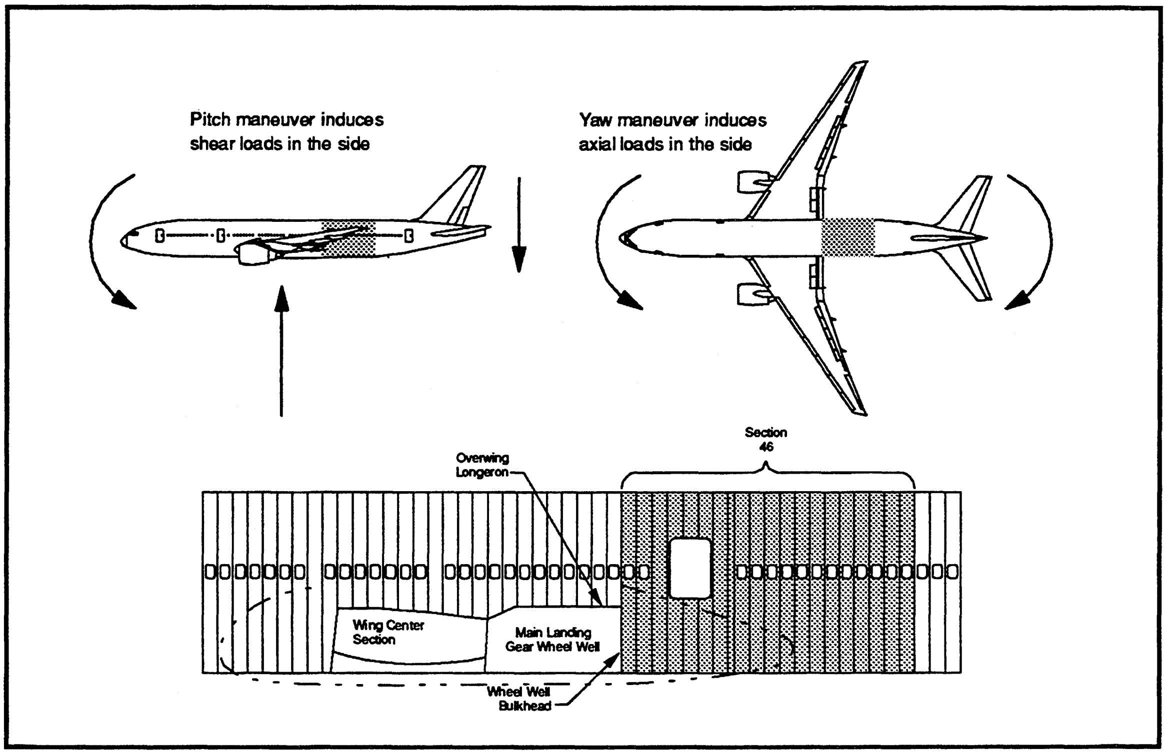


Figure 8-23. Side quadrant load paths.

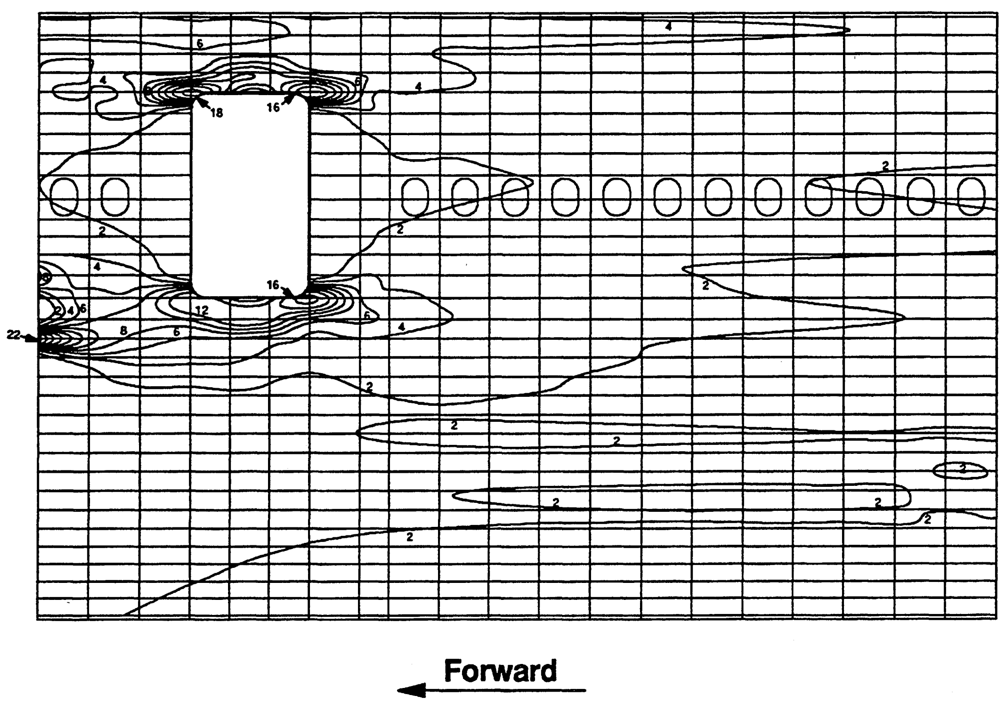


Figure 8-24. Side quadrant maximum axial tension loads (kip/in).

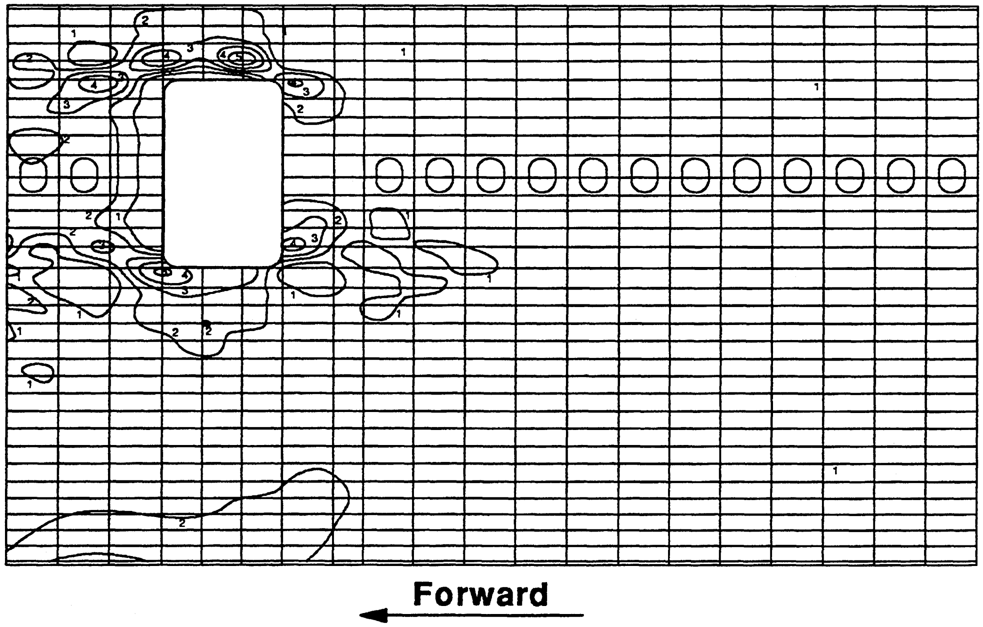


Figure 8-25. Side quadrant maximum shear loads (kip/in).

Three ULTIMATE load conditions were used to size the structure for strength and stability. The first includes flight loads (for all load cases), (multiplied by a factor of 1.5) in addition to cabin pressure (13.65 psi, representing 1.5 times the maximum positive pressure differential). The second consists of flight loads (for all load cases) (multiplied by a factor of 1.5) acting alone. The third considers cabin pressure (18.2 psi, representing twice the maximum positive pressure differential) acting alone.

The side quadrant design was also checked for two residual strength requirements. The first involves a circumferential crack with a length up to twice the typical aluminum structure stringer spacing. The second consists of a through penetration severing a frame and up to two skin bays. Three LIMIT load conditions are used. The first includes flight loads (for all load cases), in addition to cabin pressure (8.85 psi, representing a combination of operating and aerodynamic pressure). The second consists of flight loads (for all load cases) acting alone. The third considers cabin pressure (10.1 psi, representing 1.15 times a combination of operating and aerodynamic pressure) acting alone.

Laminate ply angles for the monocoque design were restricted to 0°, ±45°, and 90°. A minimum gage 2/4/2 laminate was required in each facesheet, and the facesheets are mirror images of one another. Additional balanced, but unsymmetric ±45° plies were allowed near the facesheet mid plane, and single 0°, and 90° plies were allowed at the facesheet mid plane.

8.3.2 Side Panel Baseline Design Trades

The initial side panel design trades focused on blending effects. The baseline facesheets were fiber placed AS4/8552 and the sandwich core was 3/16-8 lb HRP. Blending rules in

COSTADE allow the user to constrain the design to discrete areas of the design space. For example, a constraint may be placed on the facesheet layups which requires that all plies in any element originate at a common key element (i.e., the element having the thickest facesheet). This constraint allows plies to drop moving away from the key element only if they will not be needed in other more remote areas. A less severe constraint allows plies to originate at multiple key elements (i.e., allowing multiple padups in more than one area). A constraint on the core thickness may require that the total panel thickness remain constant, and a less severe constraint requires that the thickness in the hoop direction remain constant, but thickness in the axial direction may change.

Non-blended point designs were identified for each element. The point designs define the minimum possible panel weight and detect critical padup areas which aid in identifying likely key element locations. The cost/weight relationships for the initial design trades are shown in Figure 8-26. The summation of minimum weight (non-blended) point designs is presented as a lower bound on weight, no cost is indicated due to the potential manufacturing and structural infeasibility of non-blended designs. The cost and weight estimates for the monocoque portion of the global evaluation sandwich design concept are included for comparison. Note that the total design developed in global evaluation includes door surround structure and window cutout details. The cost projections for all designs are based on AFP machine time cost for the sandwich facesheets, and the material cost for the facesheets and core. The core machining cost was not included because it was found to be constant with respect to the area of core material for the given configurations. Note that the manufacturing risk associated with the "constant hoop thickness" and "variable panel thickness" designs may result in an increase in manufacturing cost. The weight estimates include only that associated with facesheets and core.

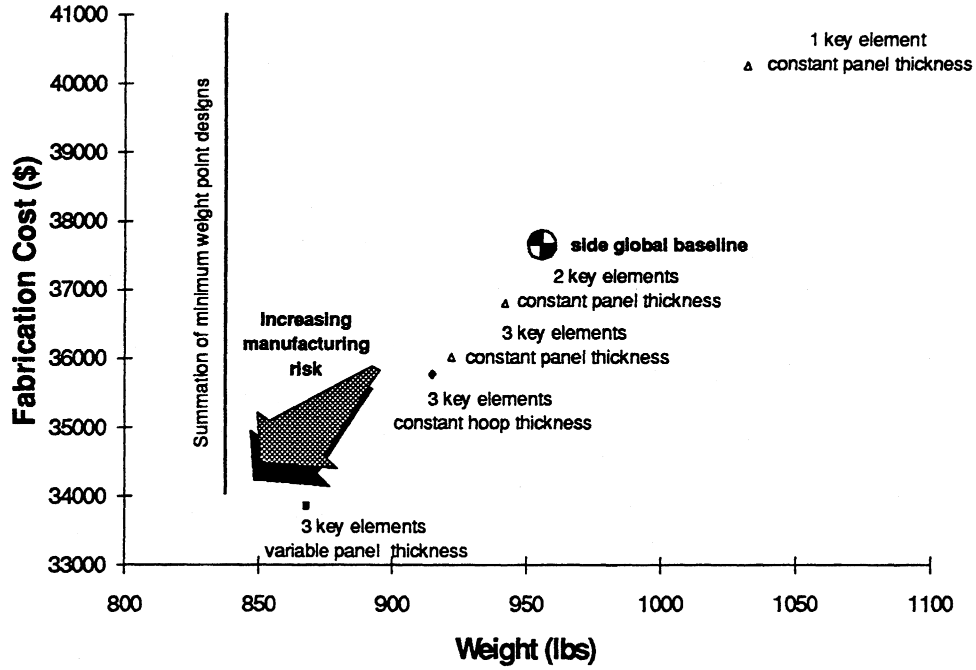


Figure 8-26. Cost/weight relationships for side panel designs.

Proximity of the side global evaluation (Figure 8-26) and the local optimization results for a constant panel thickness is evidence that the side panel cost, manufacturing and analysis databases have been successfully captured. The global baseline point falls between COSTADE blended designs for one and two key elements. (See Ref. 36 for a complete discussion of the global baseline and a comparison with the equivalent aluminum structure.) The enhanced blending routines for multiple key elements appears to help further optimize the cost and weight. The apparent advantage for local skin padups and non-constant thickness sandwich panels will depend on future manufacturing assessment of the cost of added process steps for core machining and sandwich cure processing.

Initial design trades fall close to a constant cost/weight line, indicating that the baseline minimum cost design is the minimum weight design. Note that this was not the case with crown panel optimization, however similar results were seen for keel optimization. A cost break down for the 3 key element optimum design, presented in Figure 8-27, indicates that the ratio of facesheet material weight to core material weight is the same as the ratio of facesheet cost to core cost. Note that the cost components represented here are only those which are a function of the amount of material in the facesheets and core (facesheet laydown time, facesheet material cost, and core material cost). For the design configurations considered (with the current material costs, scrap rates and labor costs), the cost per pound of facesheet material is the same as the cost per pound of core material. A shift in these ratios (core cost / facesheet cost versus core weight / facesheet weight), caused by a change in material or manufacturing cost will produce distinct cost and weight optimum points. Similarly, future studies addressing the cost summation of all panel processing steps may result in different cost and weight optimum points.

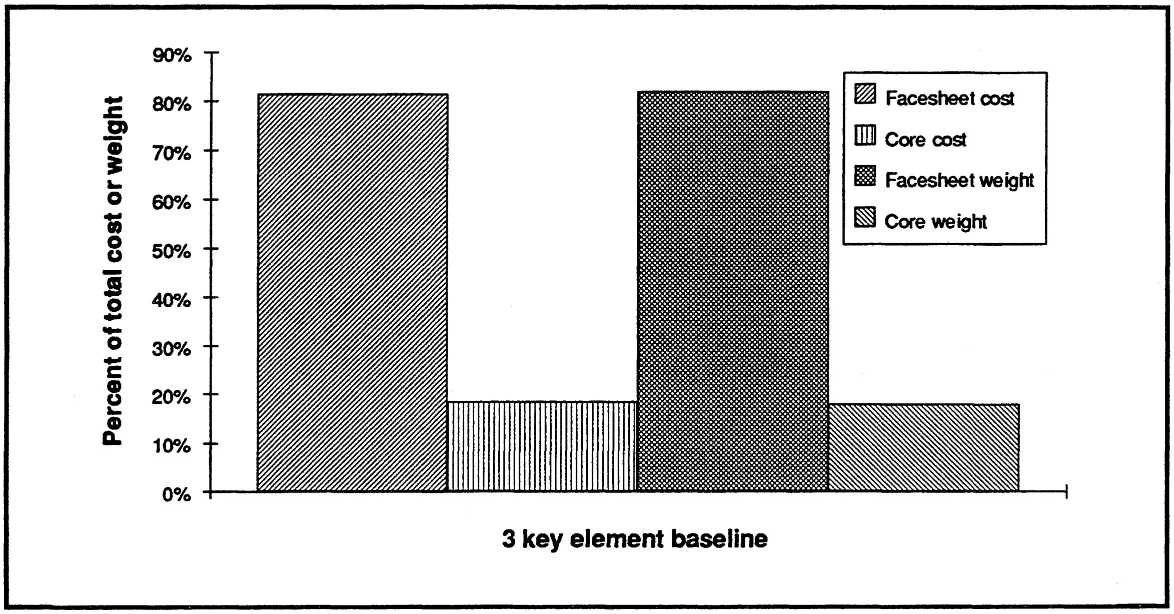


Figure 8-27. AFP cost/weight break down.

Figure 8-28 shows the total number of plies in each facesheet for the non-blended point designs. The numbers on the top of the columns correspond to the design element number. Three padup areas are indicated, elements #2 or #3, #11, and #22. The core thickness for the non-blended point designs show a significant variation over the surface of the panel, resulting in a non-constant panel thickness, Figure 8-29. Non-blended point design features in Figures 8-28 and 8-29 present both cost and structural performance problems associated with manufacture and attachment of the fuselage circumferential frames. Unique frames, with a changing radius of curvature, are required to match a variable IML skin surface. The unique frames require additional tooling and the changing radius of curvature produces panel cure and assembly difficulties which may result in a higher scrap rate. A mismatch at the frame-skin interface may also reduce the integrity of the bondline. The COSTADE blending rules can be used to constrain the design space to areas which avoid these manufacturing problems.

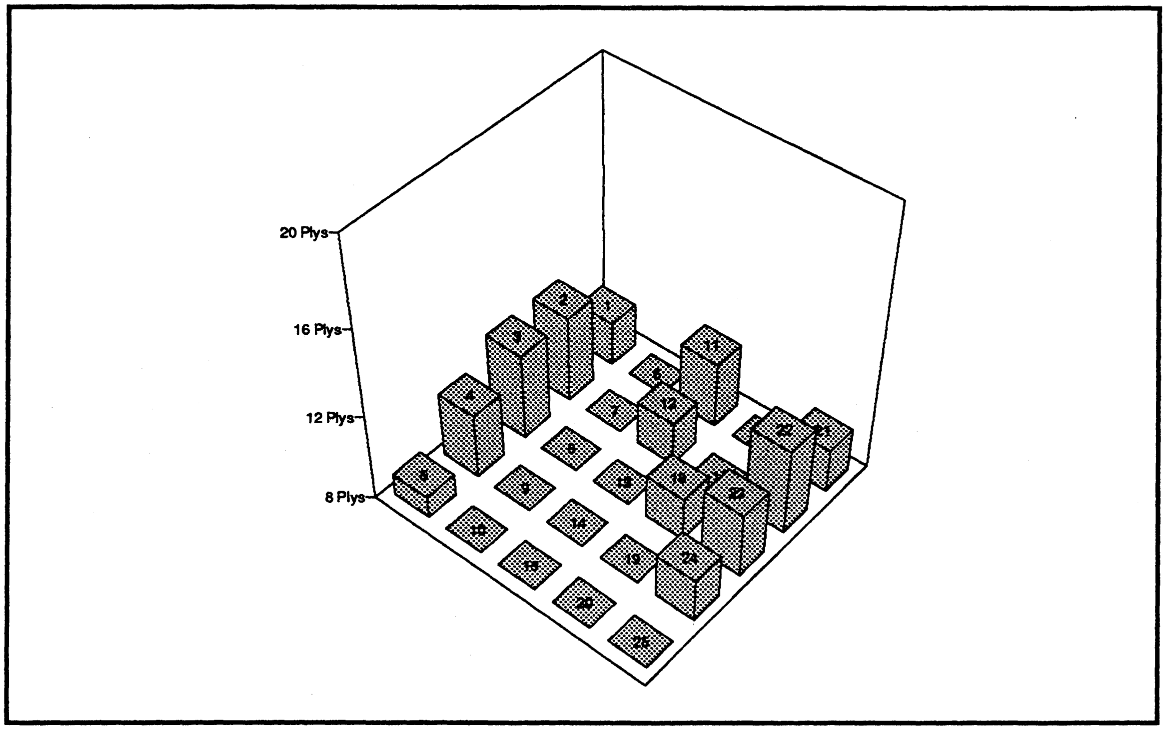


Figure 8-28. Facesheet ply count, non-blended point designs.

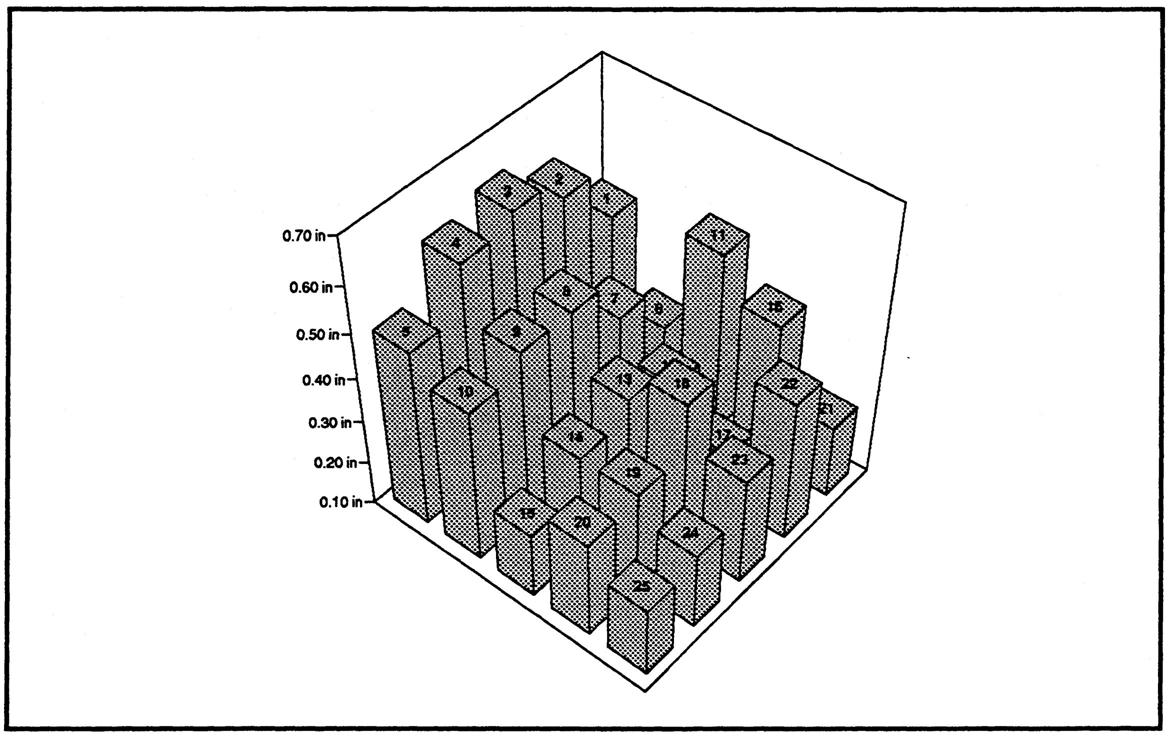


Figure 8-29. Total sandwich thickness, non-blended point designs.

The 1 key element blended design forces all plies to originate in element #3. This design has a weight increase over the minimum weight non-blended design of 23%, as shown in Figure 8-26. Note that this is a higher penalty than that found during blending of a skin/stringer crown panel (Ref. 11). However, the side panel load conditions, having multiple peak load locations, are more complex than the crown panel loads. Additionally, the constant panel thickness requirement adds additional core to many of the elements. Figure 8-30 shows the total number of plies in each facesheet for the 1 key element blended design. The core thickness in each design element is proportional to the inverse of the facesheet thickness, resulting in a panel with a constant overall thickness. The minimum margin of safety for each design element is given in Figure 8-31. The elements at the center of the panel are forced to carry more plies than necessary, ensuring that there are enough plies available in the design elements along the top row of the panel (elements #21 through #25).

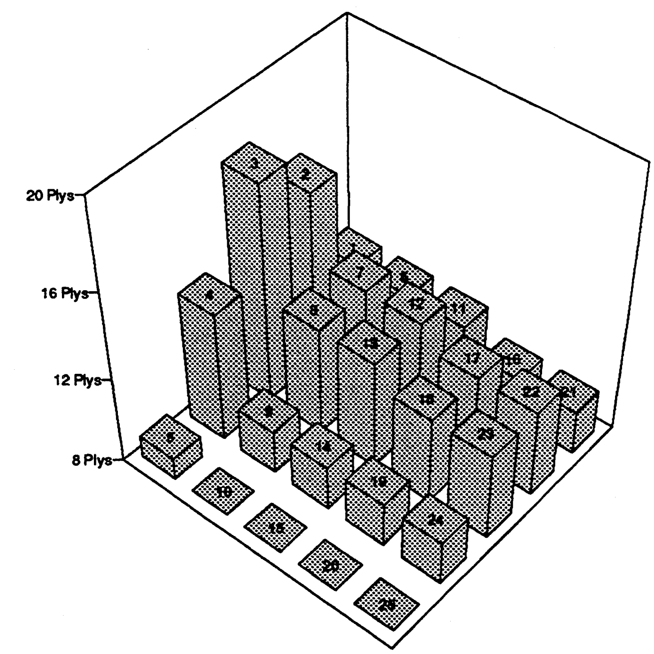


Figure 8-30. Facesheet ply count, blended design, 1 key element.

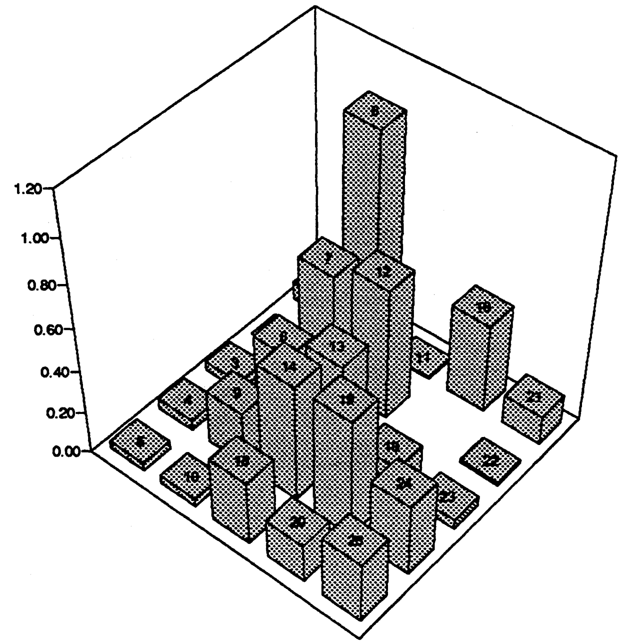


Figure 8-31. Minimum margins of safety, blended design, 1 key element.

The multiple key element option in COSTADE provides a more reasonable approach to blending, considering the potential of AFP and automated core machining equipment. A minimum number of plies that are continuous across the panel is defined. In the current example, a 2/4/2 base laminate is required in each facesheet. A two key element blended panel is defined using design elements #3 and #22 as key elements. Figure 8-26 indicates a 12.5% weight penalty over the minimum weight non-blended point designs.

Another multiple key element panel is defined using design elements #3, #11, and #22 as key elements. The three key elements correspond to locations of highest load concentration. Figure 8-26 indicates a 10.1% weight penalty over the minimum weight non-blended point designs. The ply count for each facesheet is shown in Figure 8-32, and the minimum margins of safety are given in Figure 8-33. The ply padup configuration is similar to the non-blended point designs, suggesting that the optimum configuration of key elements has been selected. The 10.1% weight penalty in the 3 key element design consists of a 5.7% component in core weight and a 4.4% component in facesheet weight. The magnitude of the blending weight penalty is similar to that found in previous studies. The critical design drivers for each design element are displayed in Figure 8-34. Note the complex interaction of design criteria, from tension based criteria in the upper portion of the panel, to compression driven criteria in the lower portion. The total panel thickness is defined by an ultimate load buckling constraint in element #2. Effects of this constant thickness constraint are addressed in the next example.

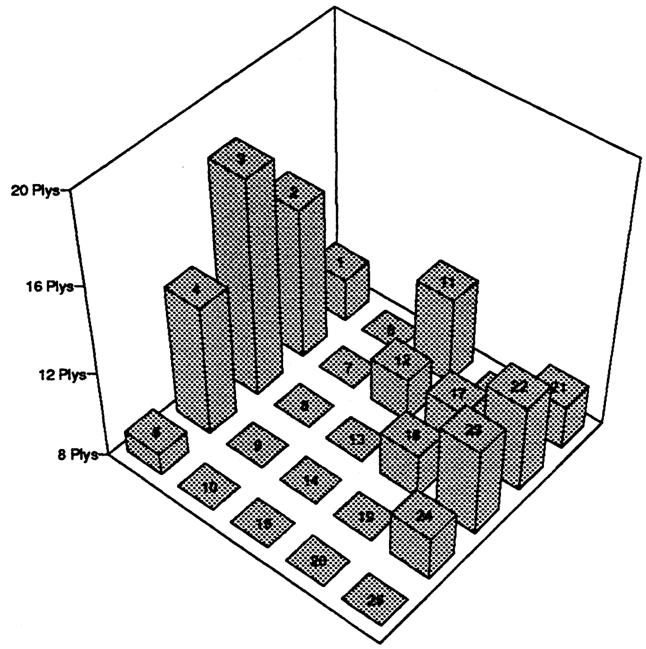


Figure 8-32. Facesheet ply count, blended design, 3 key elements.

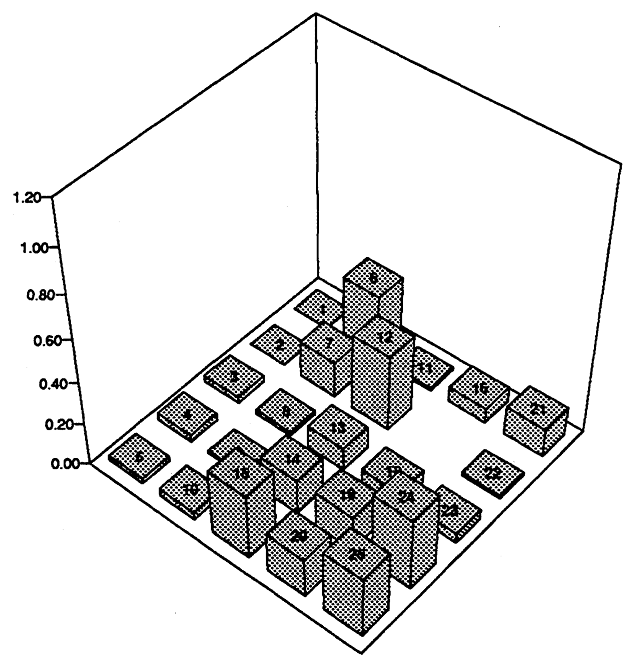


Figure 8-33. Minimum margins of safety, blended design, 3 key elements.

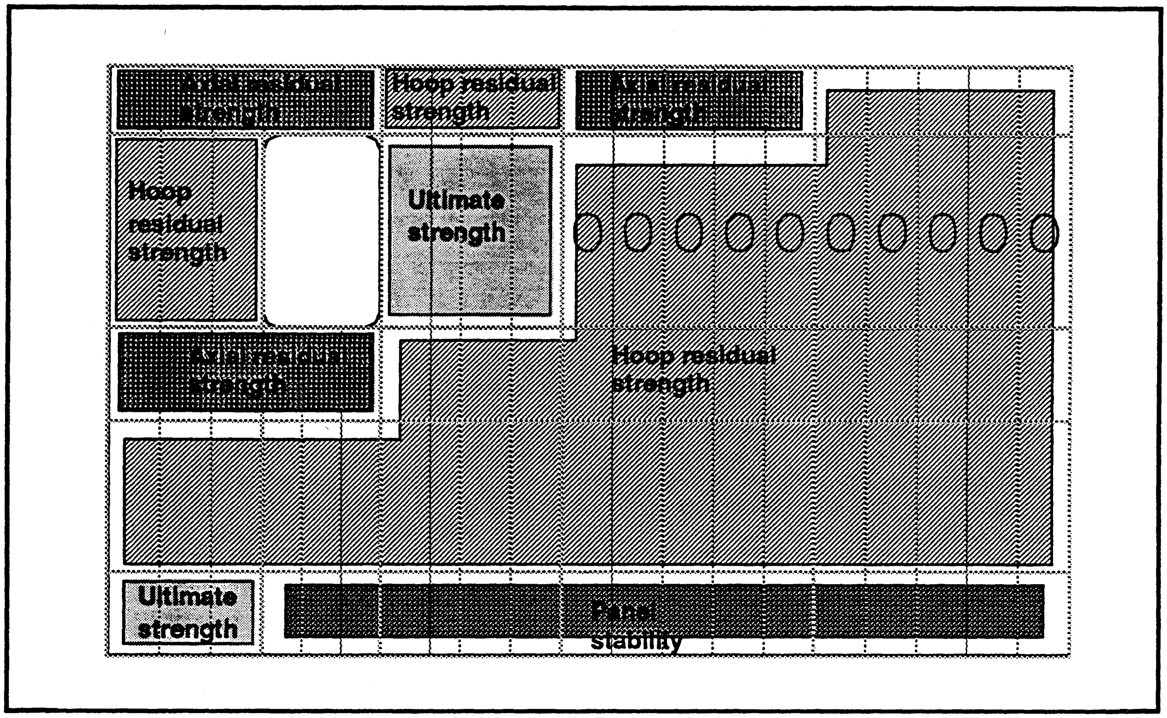


Figure 8-34. Design drivers, blended design, 3 key elements.

The "constant hoop thickness" design, shown in Figure 8-26, corresponds to a sandwich panel with constant thickness in the hoop direction, but a variable thickness in the axial direction. The thickness of each sandwich hoop band is defined by the ultimate load buckling constraint on one element in the column. A very small weight advantage is gained with this design, as the ultimate load buckling constraint was near critical values for many elements in the 3 key element blended design. The risk in the cost calculation for this design is significantly higher, because it does not include panel cure processing steps. Unique frames and unique tooling are required to match the changing IML panel surface. This added complexity may increase the process cost and scrap rate for this design configuration. As a final design trade, the constant radius of curvature frame constraint is removed. Future efforts to add more process steps to the cost equations would likely result in a significant increase in the cost of this design.

8.3.3 Side Panel Material Design Trades

Design trades for the baseline configurations indicate that the minimum cost and minimum weight designs are identical. This commonality is a result of the reduced number of process steps considered and nearly equivalent cost per pound for facesheets and core. As relative material or manufacturing cost change, distinct cost and weight optimum points appear. For example, a change in the core material cost shifts the minimum weight design up or down, as shown in Figure 8-35, however, the minimum cost designs have different configurations. Figure 8-36, shows that the weight of the minimum cost design is a function of core material cost. Two core-cost trades are presented, 4 times the baseline cost and 1/4 of the baseline cost. As the core cost decreases relative to the facesheet cost, additional core material is added to replace facesheet material, and likewise, as core cost increases relative to facesheet cost, core material is removed and replaced with facesheet material. The sloping lines on the plot represent equivalent value designs for a weight savings payoff of $100 per pound of material saved.

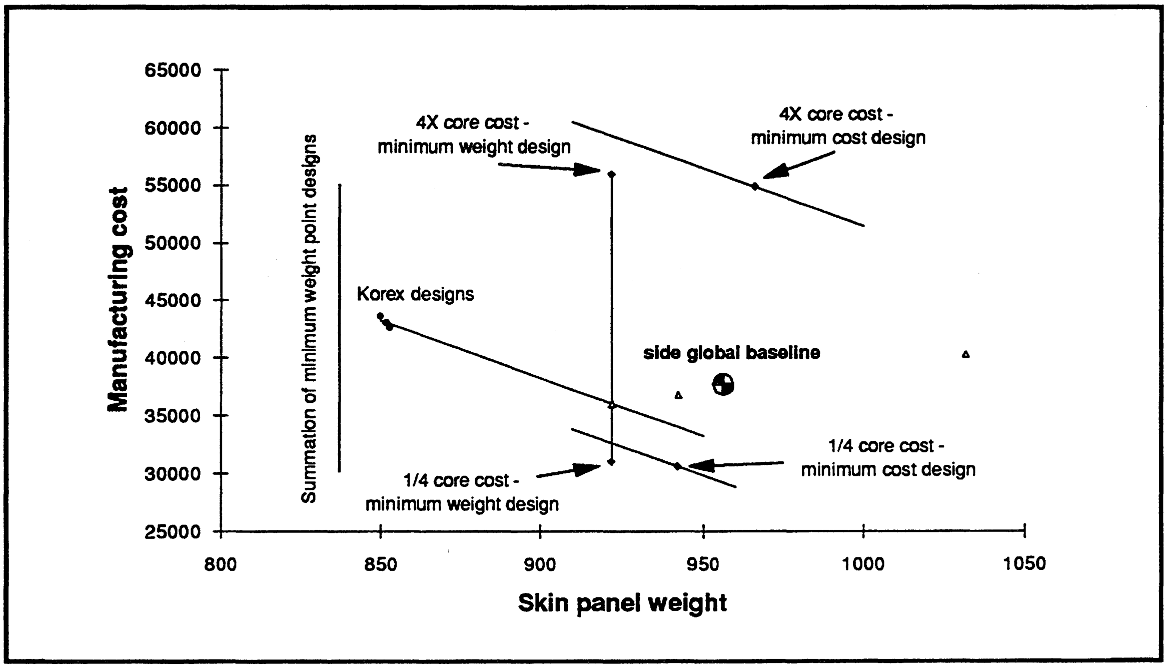


Figure 8-35. Side panel material trades.

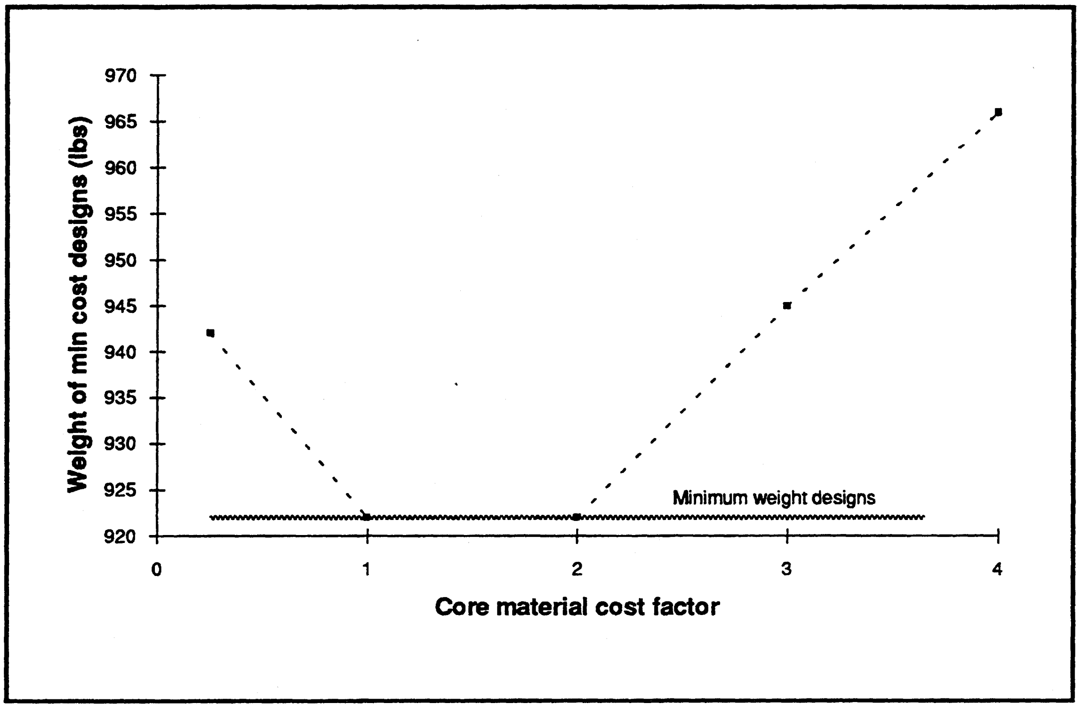


Figure 8-36. Core material cost/weight trade.

A second material trade is shown in Figure 8-35, for Korex, a core material having similar mechanical properties with lighter weight but higher cost. The minimum cost and minimum weight designs have distinct configurations. This is expected, as the cost per pound to place facesheet material is different than the cost per pound for core material. When compared with the 3 key element baseline design and the $100 per pound curve, the Korex designs show a slightly better value, and thus justifies the move to a more expensive material. If the weight savings payoff increases above $100 per pound of material saved, the Korex designs become even more attractive.

8.3.4 Side Sensitivity Study Summary

Since the previously discussed side sensitivity study was performed, more refined COSTADE models (220 versus 25 design elements) have been assembled. These refined cost models and analyses (with cutouts and splices) have been incorporated into the software.

8.4 Fuselage Barrel Cost Analysis

Refinement of the fuselage barrel design, by considering interactions of the quadrant designs with the barrel rather than refining individual quadrants separately, has been initiated (Ref. 26). This section contains a summary of barrel costs for the baseline composite fuselage barrel as predicted at the end of phase B. The associated designs result from DBT interaction and not just from COSTADE optimization runs.

The current fuselage cost model database is summarized in Figure 8-37.

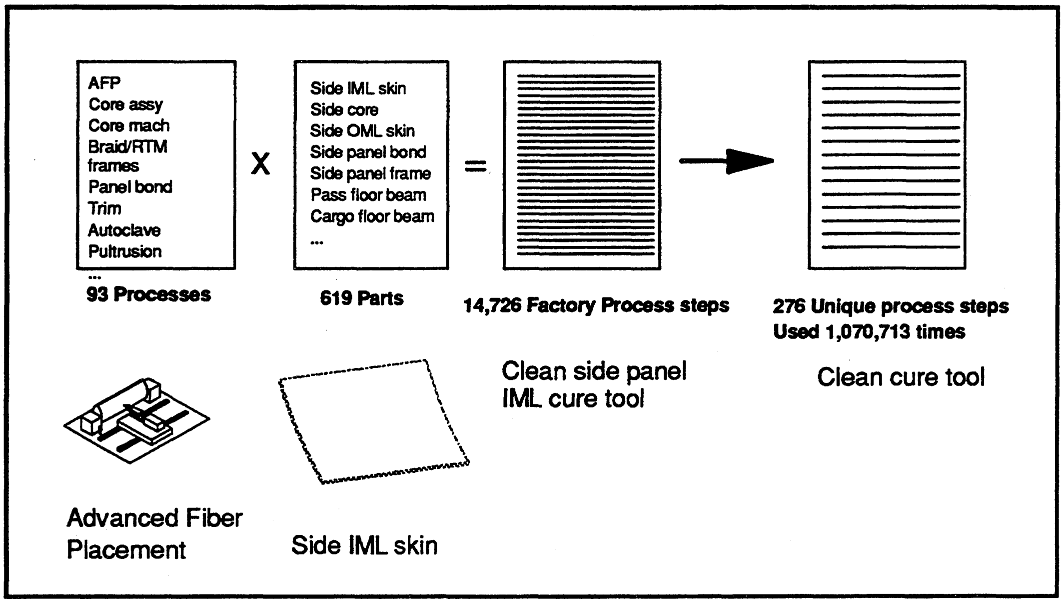


Figure 8-37. Current fuselage cost model database.

The ATCAS phase B barrel cost summary is shown in Figure 8-38. Eighty percent of the total fabrication costs have been captured in the cost model. The bulk of "other" costs are made up of door fabrication and details associated with installation, splices, and window frames.

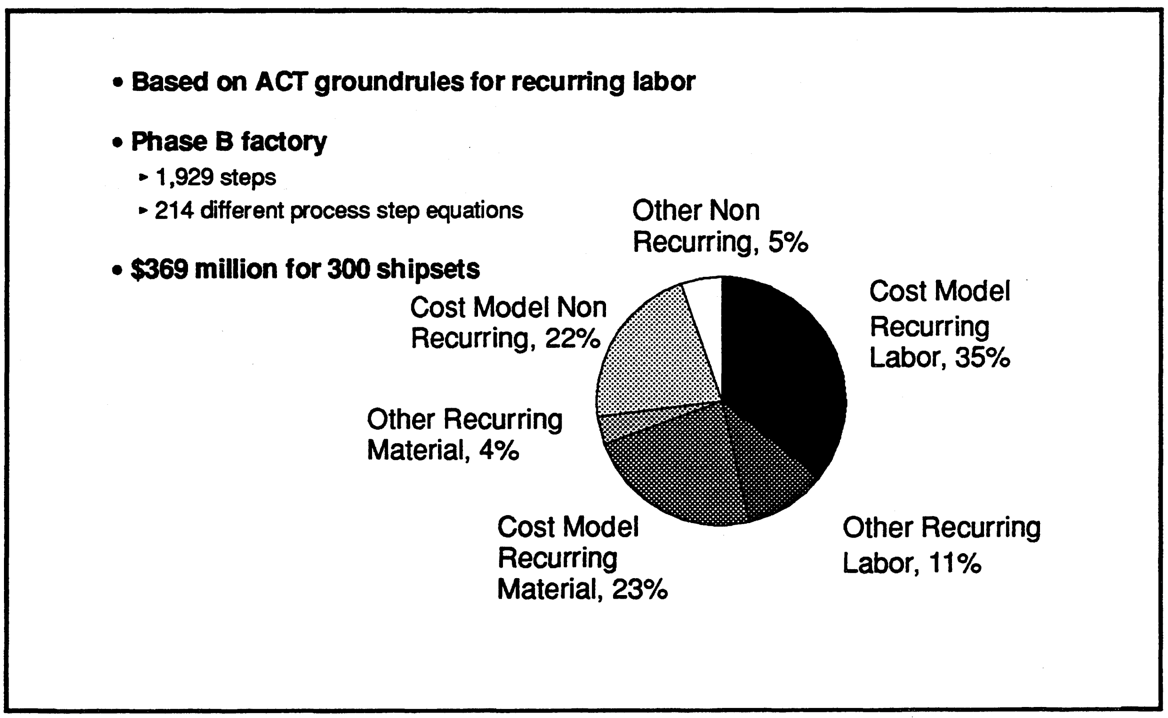


Figure 8-38. ATCAS phase B full barrel cost summary.

As equations are evaluated for each process step (1929 in current phase B full barrel model) a great deal of data is available and can be sorted in many ways. The ability to sort this detailed data is one of the strengths of the approach. Design/Build teams now have the ability to understand where costs originate and have options to minimize them. Readily available automated sorting tools are required to support this activity.

In order to give a rough indication of the fidelity of process step cost equations and factory equation sets, recurring labor costs, number of manufacturing step equations and average cost per equation associated with major processes are shown in Figures 8-39, 8-40, and 8-41. These figures can help guide the design/build team on which major processes (in very general terms) need refinement relative to the others. The fidelity of each individual equation can influence accuracy. For example if one cost equation can properly represent automated fiber placement for all zero degree plies in an entire model including the effects of all strip start and stops (Ref. 3 and 14), no refinement may be necessary even though this equation may represent a relatively large cost.

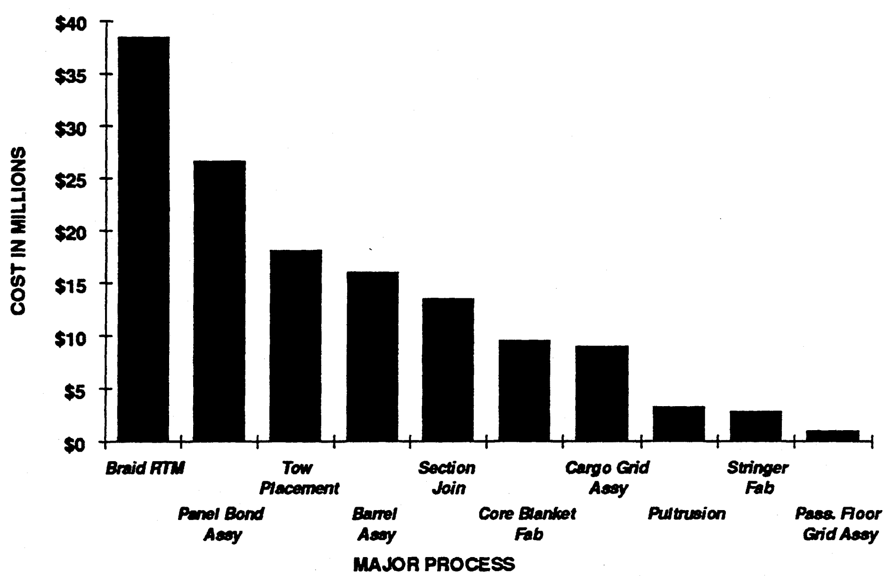


Figure 8-39. Recurring labor cost associated with major processes for ATCAS phase B barrel.

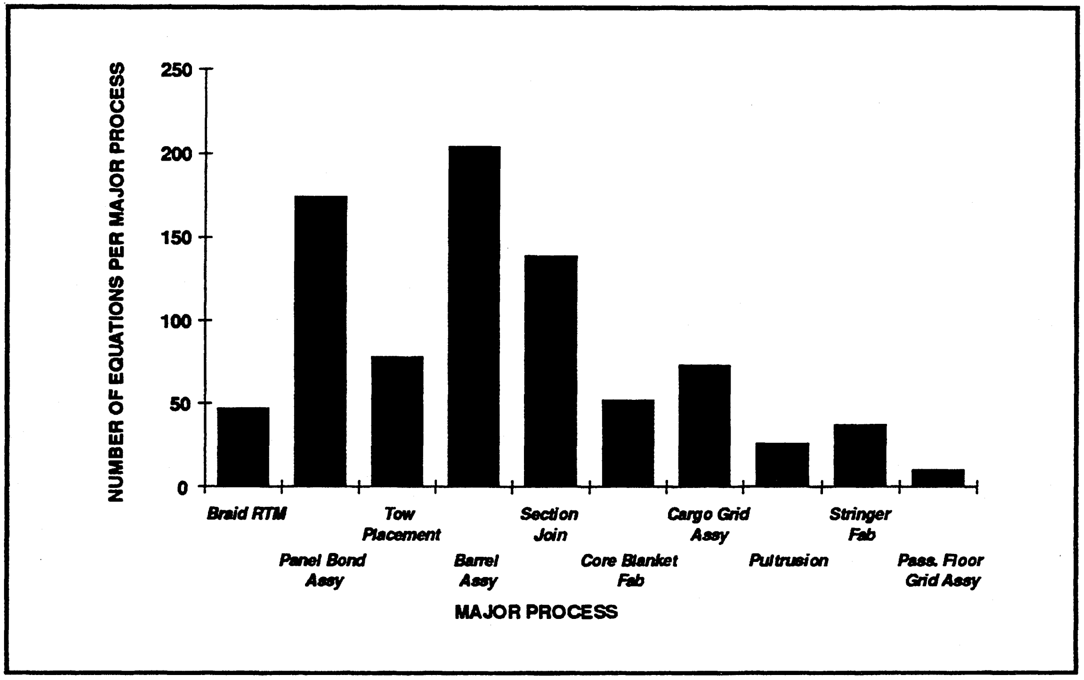


Figure 8-40. Number of equations for recurring labor for each major process for ATCAS phase B barrel.

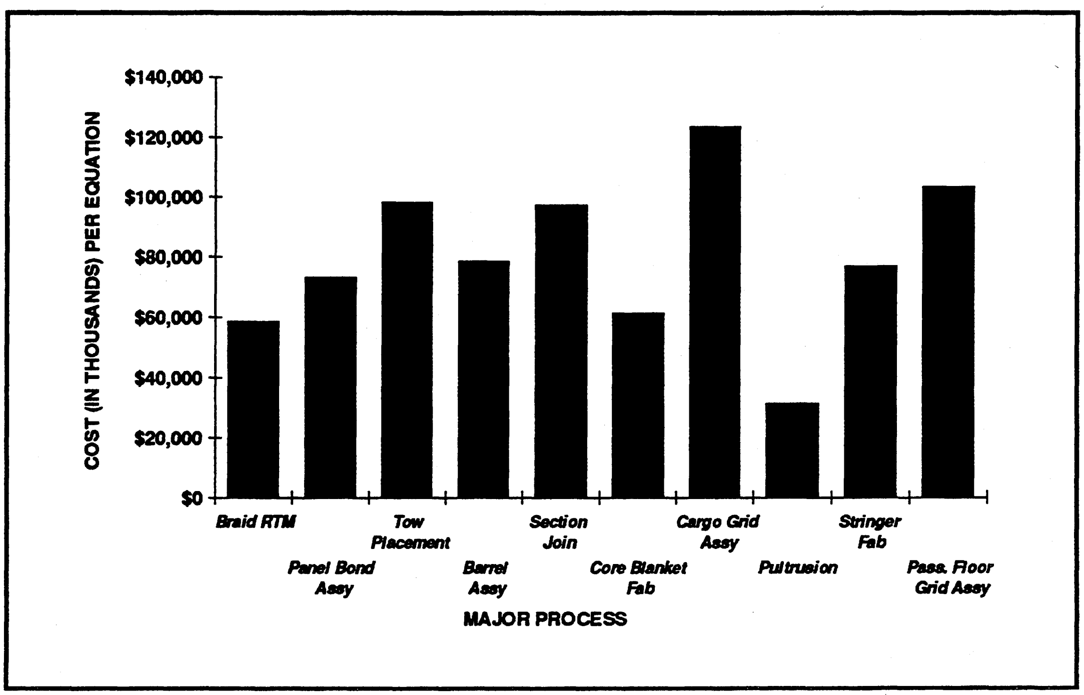


Figure 8-41. Average cost per equation for recurring labor associated with major processes for ATCAS phase B barrel.

The factory equation set of the 1929 process steps used to generate the cost estimate required the use of 214 unique process step equations as shown in Figure 8-42. Some of the cost equations had more influence on the total estimated cost of than others. Roughly a third of the cost equations were responsible for over 80 percent of the estimated recurring labor cost of the design. The most significant individual process step equations of the 214 used to represent the ATCAS phase B factory are shown in Figure 8-43. The top ten process step equations represent 6.6 percent of the 1929 steps and 22 percent of the recurring labor cost. One of the cost equations was the drilling of countersunk holes. A graphical representation of this equation is shown in Figure 8-44. Fully 95 percent of the cost predictions were contained within a narrow range of the design space for this equation. The accuracy of the drilling estimate is strongly dependent on the accuracy of the cost equation within this range.

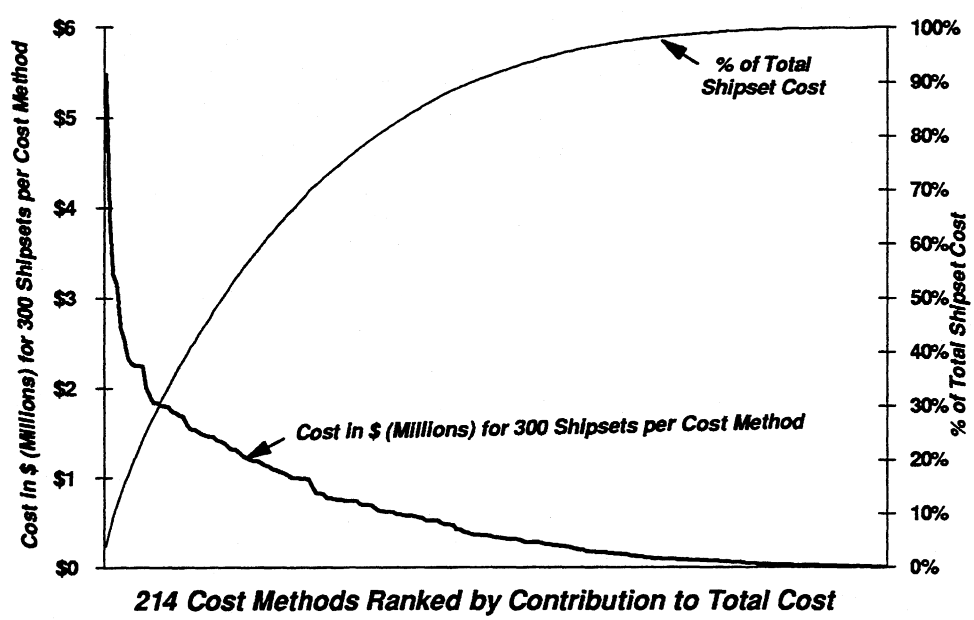


Figure 8-42. Process step cost equations.

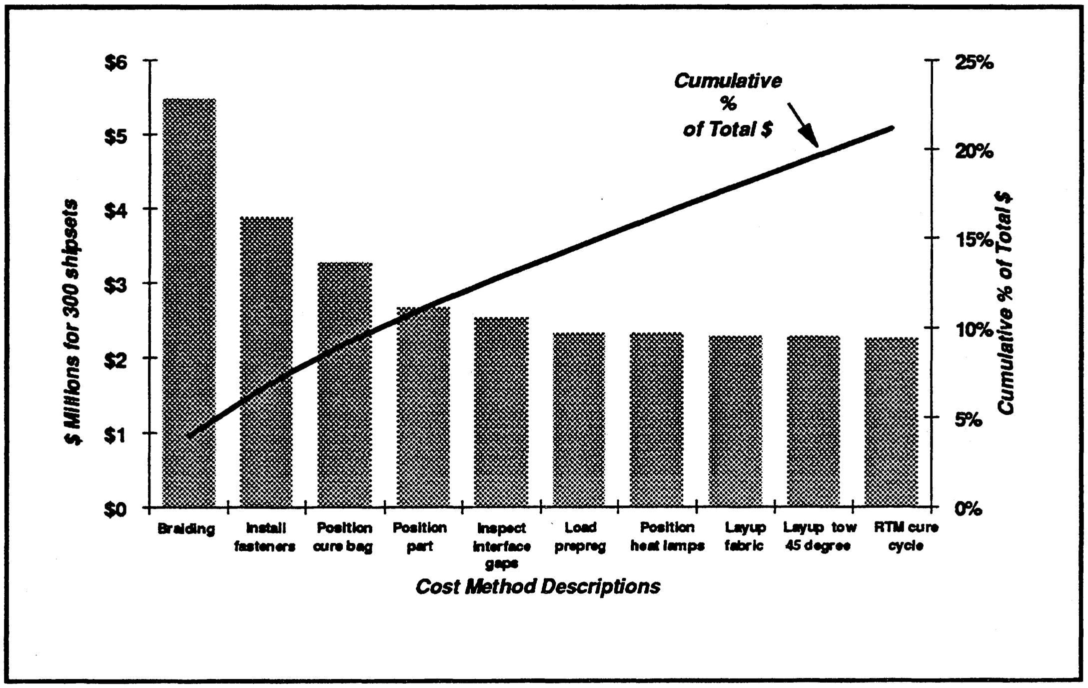


Figure 8-43. Top ten process step cost equations.

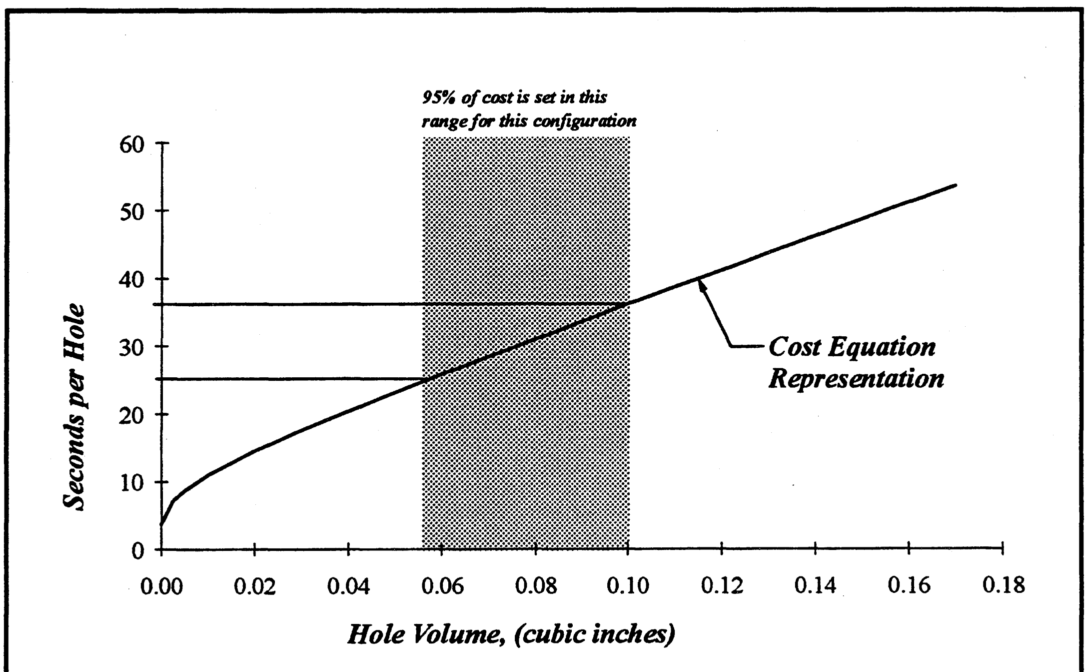


Figure 8-44. Drill and countersink holes - graphite/epoxy.

The most significant part definition values can be identified by sorting the cost model output and viewing the top fourteen grouped part definition values as shown in Figure 8-45. These grouped part definition values are associated with 100 percent of the total costs. Many may be interrelated (e.g. part length and part perimeter) and therefore care must be taken to properly interpret the data.

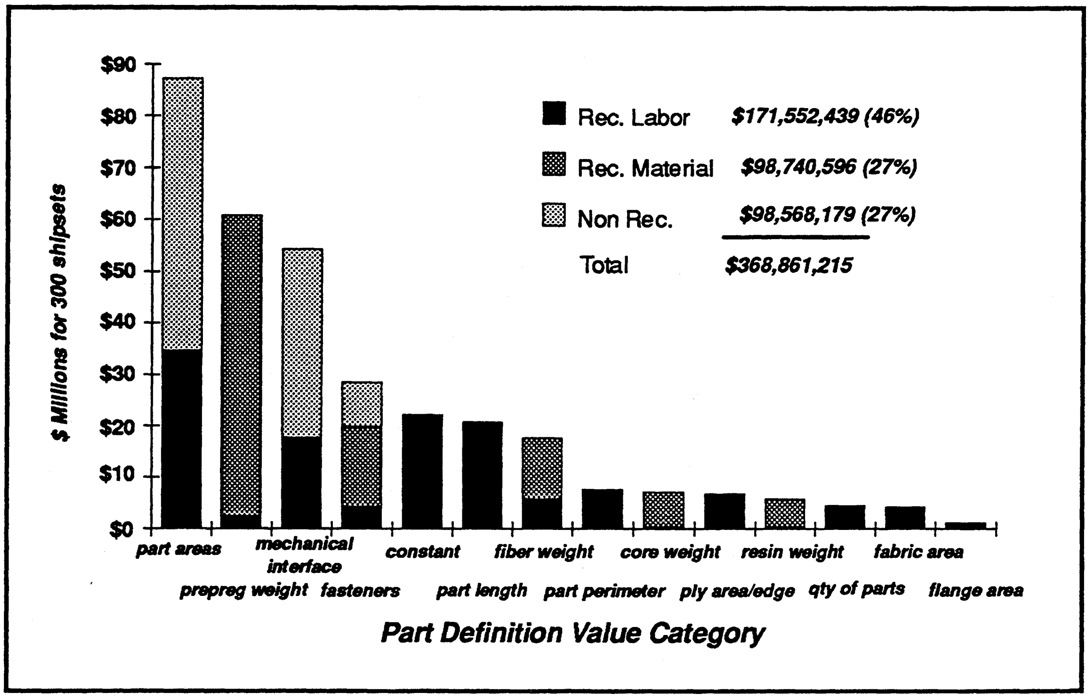


Figure 8-45. Top fourteen grouped part definition values.

Figure 8-45 also attempts to illustrate the costs associated with major groups of part definition values. Note that configuration and panel sizes (i.e. part area) are fixed early in the structural development effort, whereas the others are fixed later on. Because this graph is valid only for the specific design evaluated and the specific processes chosen, a change in process or design will change the graph. The cost equations and coefficients associated with fixed design features are as important to be validated as cost equations and coefficients with more design flexibility.

Successes in the use of these cost model methods on the ATCAS program have resulted in preliminary cost studies using these methods to be performed internally at Boeing. These initial applications of this new capability resulted in consistent cost estimates produced in a fraction of the time required for traditional techniques.

9.0 RECOMMENDATIONS FOR FURTHER DEVELOPMENT

From experience gained in developing and using COSTADE, the most reliable indicators for future development efforts come by attempting to apply the code to actual problems. Other than the applications having more priority than the other topics, the following list is not prioritized:

9.1 Applications

1. Perform an ATCAS fuselage barrel sensitivity study including bi-directional loads model link. This study would identify coupling of design changes in various areas in the barrel to influence the designs in other areas (e.g. increased crown stiffness may reduce keel loading). Ref. 26 documents the initiation of this study.

2. Perform sensitivity studies and design optimization of structure other than composite fuselage (wing, empennage, strut, conventional aluminum, etc.) These studies will guide the development of COSTADE for more diverse aircraft structures.

3. Evaluate design details such as door surround structure, window belt padups and splice details. This study would help to define how local design details influence total panel configurations.

9.2 Cost Model

1. Refine the process step equations in phase C. Data gathered during the fabrication of phase C parts will provide increased confidence in the process step equations.

2. Refine the factory equation sets in phase C. Data gathered during the fabrication of phase C parts will provide increased confidence in the factory equation sets.

3. Develop aluminum structure cost equations. Comparisons of costs associated with advanced processes to current processes is required in order to decide whether the advanced ones are cost effective. The prediction methods used for each scenario must be consistent to ensure that proper comparisons are made.

4. The discretized cost modeling methodology should be developed further. The design representation in COSTADE (i.e. no variations within discrete design elements, design changes occur only at design element boundaries) is a new way of presenting designs to cost models. Representation of designs in this way is routine in structural analysis.

5. Resource costs should be developed separately for each process step to ensure that representative costs for all resources are predicted. The ACT ground rules may need to be modified to allow this to occur.

6. A representation of operating costs should be developed. The current approach has been to allow cost/weight trades to be easily accomplished if the value of weight saved is

known. The actual calculation or modeling of operating costs (e.g. fuel, maintenance, repair) would be beneficial however may prove difficult to accomplish.

7. The link from the relational database to COSTADE should be developed further. Enabling the relational database to provide all required cost information (i.e. material cost equations plus design relationships required by the cost equations), without any manual intervention, would reduce engineering time further. This item is closely related to Cost item #4.

8. Factory flow modeling should be added in order to better estimate the numbers of tools required to meet production rate requirements.

9.3 Structural Analysis

1. The load representations within each design element in COSTADE should be made compatible with major finite element based loads models that provide the internal loads. This is required to accomplish Applications item #1. Non CPU intensive procedures to predict load sharing between frames, skins and stringers for all load cases are necessary. The development of some of the required procedures has occurred as part of phase B. Modifications to the methods used to build finite element internal loads models may also be required.

2. The detailed stress analysis algorithms can be included to analyze such items as ply drops and stress concentrators in a more rigorous manner. Activities in this area are ongoing, by graduate students, at the University of Washington.

3. The inclusion of analyses required for wing, empennage, strut, conventional aluminum structures would enable COSTADE to be used to size these types of structures and would be required to accomplish part of Applications item #2.

9.4 Other

1. An improved software framework that enables easier enhancements would be beneficial. Different structures obviously require different analysis procedures to be used for evaluation and optimization. The ability to insert new methods and algorithms is necessary to allow COSTADE to be used to develop general structures. COSTADE has been written in FORTRAN, using various software development tools, configuration control methods and is well documented internally with comment statements. Relatively general modifications can be performed by those having experience with large FORTRAN source codes (presently approximately 100,000 lines). Modifications to the present code for non experienced FORTRAN users is difficult. Because the COSTADE cost algorithm allows relatively general cost models to be read in from external files, this software framework discussion does not apply to cost analyses.

2. Links between COSTADE and CATIA (the primary CAD system used by Boeing Commercial Airplane Group) may be beneficial. Initial investigations of producing International Graphics Exchange Standard (IGES) files in COSTADE and reading them

into CATIA have been performed and appear feasible. However the representation of the design using discrete design elements in COSTADE complicates matters (see Cost item #4) when considering links from CATIA to COSTADE. All factors affecting the appropriate mesh size required in COSTADE are not contained in CATIA. These same issues are encountered when developing structural finite element models based only on geometry contained in Computer Aided Design (CAD) systems.

3. The ability to use non rectangular design elements would enable more general designs to be represented in COSTADE. The architecture of the present code is compatible with this modification and initial studies have been performed that indicate that this change can be readily accomplished. Non rectangular designs required by Applications item #2 can already be handled to some extent.

4. The inclusion of aerodynamic analyses for lofting modifications would enable optimization that includes changes to the external configuration to be performed.

5. A graphical user's interface for COSTADE may be useful in aiding users when inputting the required information to define an evaluation or optimization procedure. This interface would most likely be written in C++ or Visual Basic. Several file formats are already available to allow the graphical display of COSTADE output in existing finite element pre/post processors (PATRAN), and spreadsheet applications. The input structure for COSTADE has been developed with the intention of adding a graphical user's interface for problem definition. The actual computer runs for optimization of structures are normally accomplished in a batch type mode, not requiring user intervention.

10.0 CONCLUDING REMARKS

COSTADE provides a new capability for design/build teams, namely practical multi-disciplinary optimization including cost predictions during preliminary and conceptual design. Initial applications of the new cost model methodology have resulted in consistent cost estimates for advanced processes produced in a fraction of the time required for traditional techniques. The present software has been developed for the ATCAS phase B fuselage structure.

Significant advances have been made in a number of areas (as shown in italics) during the development of COSTADE as discussed in the following paragraphs.

Methods for design build teams to evaluate fabrication costs (based on the influence of part definition values, manufacturing plans and process parameters) have been developed and demonstrated. This is an enabling technology for various engineering disciplines to credibly evaluate fabrication costs during a structural development effort.

Advances made in *scientific cost modeling* enable credible cost estimates to be made for processes where production data does not exist. Production data did not exist for advanced composite processes being considered by ATCAS to reduce fabrication costs. This scientific framework should help provide educational benefits to design build teams during product implementation as the cost analysis is applied to a constrained design and manufacturing space.

The development of *discretized cost analysis* allows cost estimates to be made using the same geometry as that used for structural analysis. This is an enabling technology for multi-disciplinary design including cost.

The *linking of cost analysis to design* allows fabrication cost to be used as an objective function in optimization and thereby allows cost estimates to have influence on the design early in the structural development effort. This is required for designs to be tailored to the selected processes that reduce fabrication costs.

Blending algorithms allow designers to maintain compatibility between design elements. This is essential for practical optimization of large composite panel designs with varying loading. This capability also enables cost models (which require feasible designs from a manufacturing point of view) to be used with structural evaluation tools.

The *breadth of structural analyses* used ensures structural feasibility of COSTADE designs. While no single structural analysis contained in COSTADE is significant on its own, the ability to interrogate all of the structural analyses is a requirement for practical optimization.

The *linking of COSTADE to a finite element loads* model has demonstrated the ability to drastically reduce the amount of engineering cycle time to develop optimized designs.

Use of *global optimization algorithms with integer design variables* (as well as continuous ones) was necessary for practical optimization of composite panel designs.

Development of a novel *manufacturing tolerances algorithm* was an initial step in including manufacturing tolerances in structural design development.

Practical structural optimization has been demonstrated in the development of the ATCAS composite structure by including analyses from a number of disciplines in the COSTADE software tool.

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13. ABSTRACT *(Maximum 200 words)*

Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE) is being developed as a tool to support design build teams in their efforts to achieve cost effective and feasible commercial aircraft composite fuselage structure. COSTADE is a multi-disciplinary evaluation and optimization tool that includes cost, weight, design, stress, and manufacturing modules. Fabrication costs are included early in the structural development process allowing the identification of cost-weight sensitivities. The use of this tool also reduces engineering development costs by shortening design cycle times and by providing improved starting points for more detailed evaluations.

This report presents details of the COSTADE development effort, descriptions of the major modules included in the software, and applications illustrating its use on the Advanced Technology Composite Aircraft Structures (ATCAS) program.

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