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# Application of a Design-Build-Team Approach to Low Cost and Weight Composite Fuselage Structure

L. B. Ilcewicz, T. H. Walker,
K. S. Willden, G. D. Swanson,
G. Truslove, S. L. Metschan,
and C. L. Pfahl
*The Boeing Company*
*Seattle, Washington*

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# FOREWORD

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Current program management for the Boeing ACT contract includes Ray E. Horton as Program Manager and Peter J. Smith as Technical Manager. Authors listed for this contractor report prepared portions of the document. The members (past and present) of the Boeing ACT contract team, each of whom contributed to the work described in this document, include:

Program Manager
- R. Horton
- P. Whalley

Technical Manager
- P. Smith

Principal Investigator
- L. Ilcewicz
- R. Coggeshall

Structural Design
- G. Truslove
- K. Griess
- C. Hanson

Manufacturing R&D
- T. May
- K. Willden
- V. Starkey

Material Technology
- D. Grande
- P. Grant
- C. Gunther
- M. Fedro

Cost Modeling
- K. Venters
- C. Pfahl
- D. Tervo

Operations Technology
- J. Valdez
- S. Metschan

Structural Mechanics
- T. Walker
- E. Dost
- G. Swanson

Business Management
- J. Heinemann

Technical Support
- W. Waltari
- T. Le

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# 1.0 SUMMARY

Boeing's program entitled Advanced Technology Composite Aircraft Structure (ATCAS) is focused on the application of affordable composite technology to transport fuselage. An aft fuselage section directly behind the wing-to-body intersection is used for technology development and verification purposes. Past Boeing studies, indicating strong interactions between design details and manufacturing costs, led to a decision to consider assembled structure during ATCAS concept selection. The approach used for this effort is based on a design build team (DBT). The initial goal of the DBT is to identify composite design and manufacturing concepts that have a strong potential for cost and weight savings as compared to 1995 metals technology. Relative cost and weight estimates from a new Boeing airplane program serves as a benchmark for advanced metals technology. The loads and configuration constraints for this airplane are also used for ATCAS sizing exercises.

The ATCAS schedule plans to study crown, keel, and side areas of the aft fuselage section over a five year time period ending in 1994. This report documents the three step DBT approach developed for ATCAS design activities and DBT progress to date. Progress was mainly in two areas. First, baseline concepts (DBT step #1) were selected for the entire fuselage section. Second, comprehensive cost and weight trade studies (DBT step #2) were performed for several crown panel designs, yielding data that indicated advantages for polymer composite materials over metallic construction.

# 2.0 INTRODUCTION

The NAS1-18889 contract entitled Advanced Technology Composite Aircraft Structure (ATCAS) started at Boeing on May 12, 1989. The main objective of this 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 primary structures of future aircraft with the emphasis on pressurized fuselages. Early phases of product development within ATCAS judge the merits of structural concepts by considering enough design details to get both fabrication and assembly costs. Composite concepts are compared against a 1995 metallic baseline. An accurate estimate of the potential for cost and weight savings with a composite concept is established prior to the commitment for solving major technical issues.

The ATCAS approach to achieving cost savings by focussing on design details and assembly in the early phases of product development relates to the primary cost centers in current fuselage structure. Figure 2-1 shows that assembly is a major cost center for metallic fuselage structure; it accounts for nearly half the recurring manufacturing labor costs, significantly more than the fabrication of any individual element. Details of design (e.g., reinforcement of cutouts, attachment of individual elements) strongly influence the element-fabrication and assembly costs. Although the relationships differ for composite fuselage structure, the design details and assembly continue to be major cost factors.

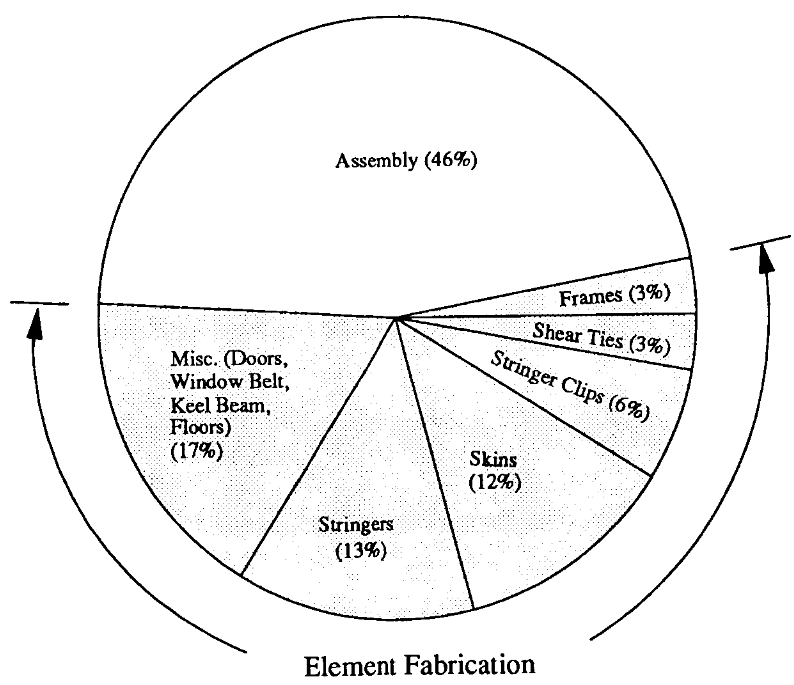


**Figure 2-1: Recurring Labor for a Typical Boeing Metallic Aft-Fuselage**



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The ATCAS program has chosen an aft fuselage section for demonstrating low-cost composite technology advancements. An exploded view of the aft fuselage section (referred to as "section 46") for the Boeing 767-200 is shown in Figure 2-2. Three major elements of the aft fuselage are being considered in the ATCAS program. These include:

1. Crown
2. Side (Including Window Belt)
3. Keel

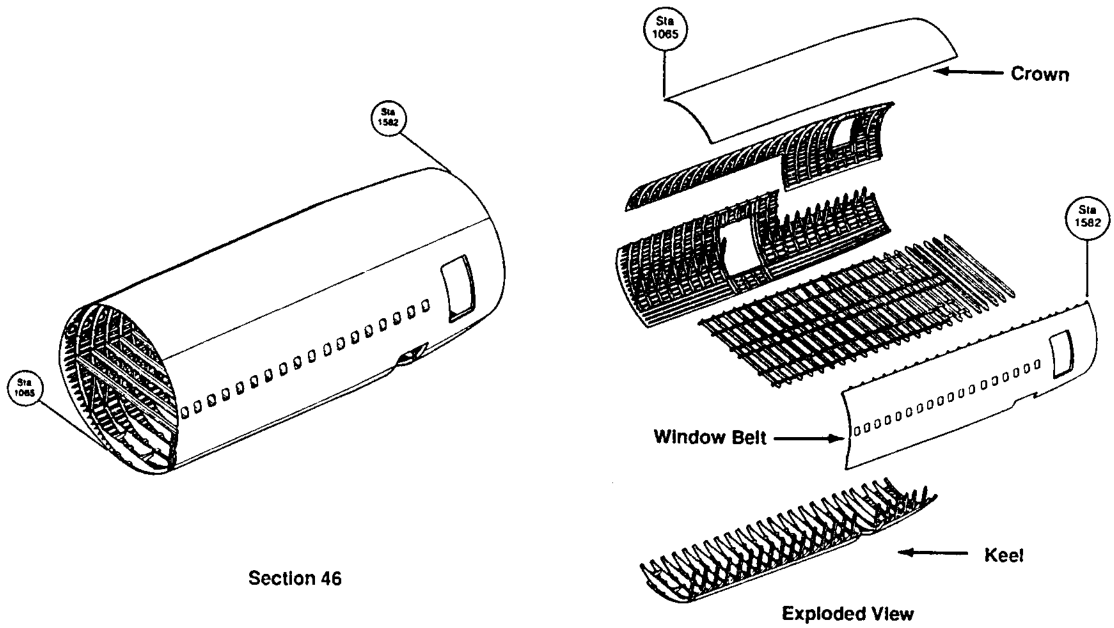



**Figure 2-2: Aft Fuselage Section 46 for the Boeing 767-200 Aircraft**

The design envelope (i.e., size, loads, and configuration constraints) chosen by ATCAS is based on preliminary data for section 46 of a 767-X sized airplane (a current Boeing aluminum commercial airplane development program). The 767-X has a fuselage diameter of 244 in. and loads characteristic of a commercial aircraft which is 80% the size of a 747 (see Figure 2-3).

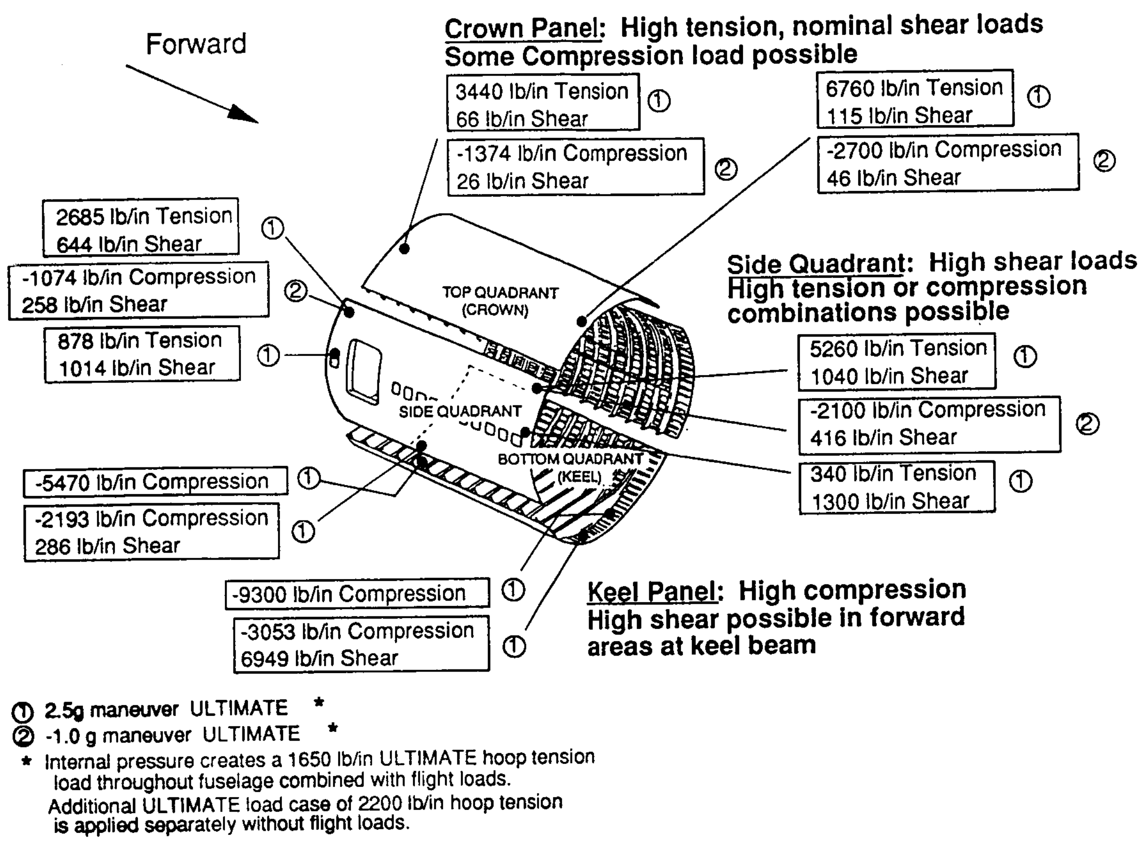



**Figure 2-3: Loading Diagram for a Composite Fuselage**

The manufacturing cost issues associated with an aft fuselage section are shown in Figure 2-4. Although some issues are common to the entire section, each area has unique problems that must be solved in order to achieve low costs. Many of the important composite structural issues, shown in Figure 2-5, are also unique to individual areas of the fuselage.

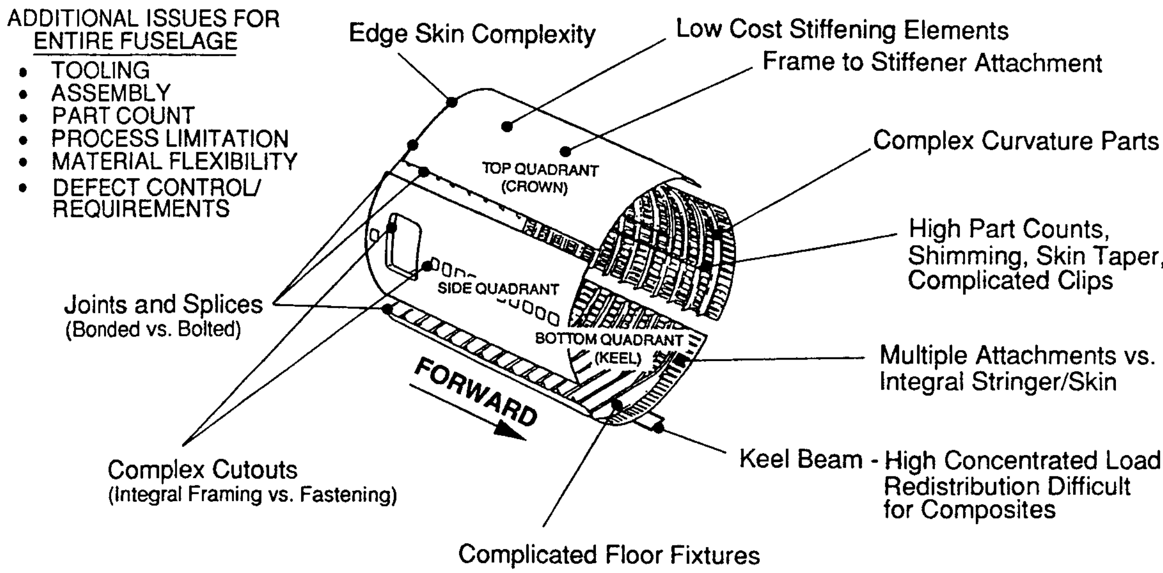



Figure 2-4: Cost Drivers for a Composite Fuselage

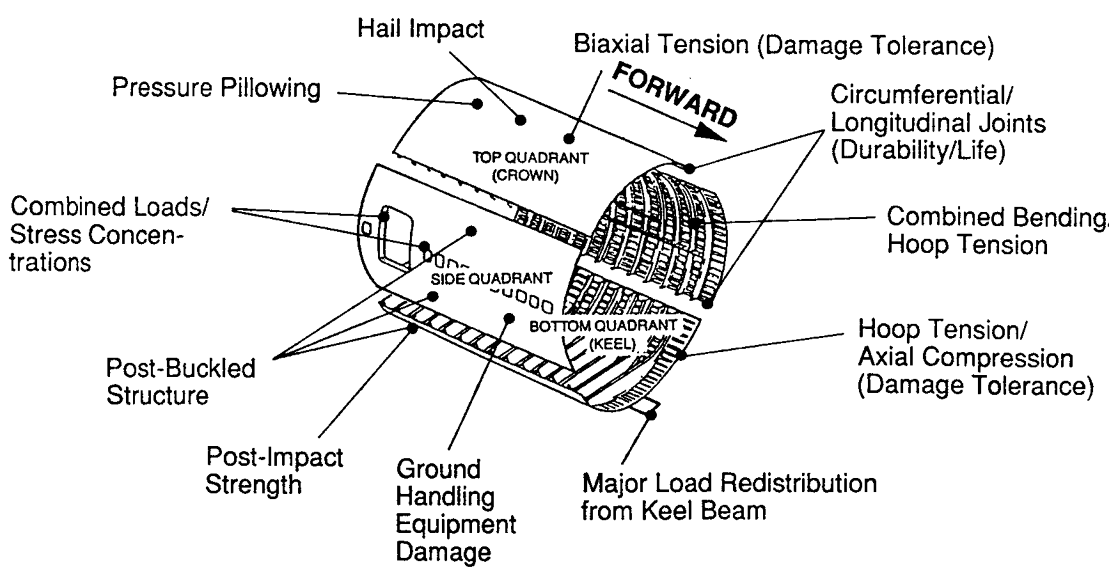



Figure 2-5: Structural Design Drivers for a Composite Fuselage

A design build team (DBT) approach is used to select structural concepts studied in ATCAS for each area of the fuselage. This approach uses a three step process: (1) baseline concept selection, (2) detailed cost and weight sensitivity studies (global optimization), and (3) subcomponent/element tailoring (local optimization).

Baseline concepts are selected during preliminary DBT reviews as those ideas having the greatest potential for cost savings, combined with an acceptable risk. During global optimization, representative detailed designs and fabrication/assembly plans are developed for the baseline and a limited number of alternative concepts. This facilitates cost and weight trades which consider enough details to select a cost-effective concept for further study. Cost centers and technology issues are also identified during global optimization. Local design optimization addresses the critical cost centers, technology issues, and structural performance details. The goal of this DBT step is to minimize cost and weight, while ensuring structural integrity.

This report is divided into three main sections. The first will discuss details of the ATCAS DBT approach, including its conception and experiences to date. The merits of baseline concepts selected for each area of the fuselage will be covered in the second section. Manufacturing and structural issues that need to be addressed during concept development and verification will also be described. The last section of this document presents cost and weight results from the ATCAS DBT for crown fuselage structure to demonstrate the global optimization design step.

# 3.0 DESIGN BUILD TEAM APPROACH

The purpose of a design build team (DBT) is to coordinate the expertise of various disciplines responsible for creating aircraft structure (e.g., design, manufacturing, cost analysis, materials, structures, quality control) at the time of concept selection. The end result of DBT interactions is expected to be cost savings by selecting concepts that can be built using efficient manufacturing processes. This form of concurrent engineering is shown schematically in Figure 3-1.

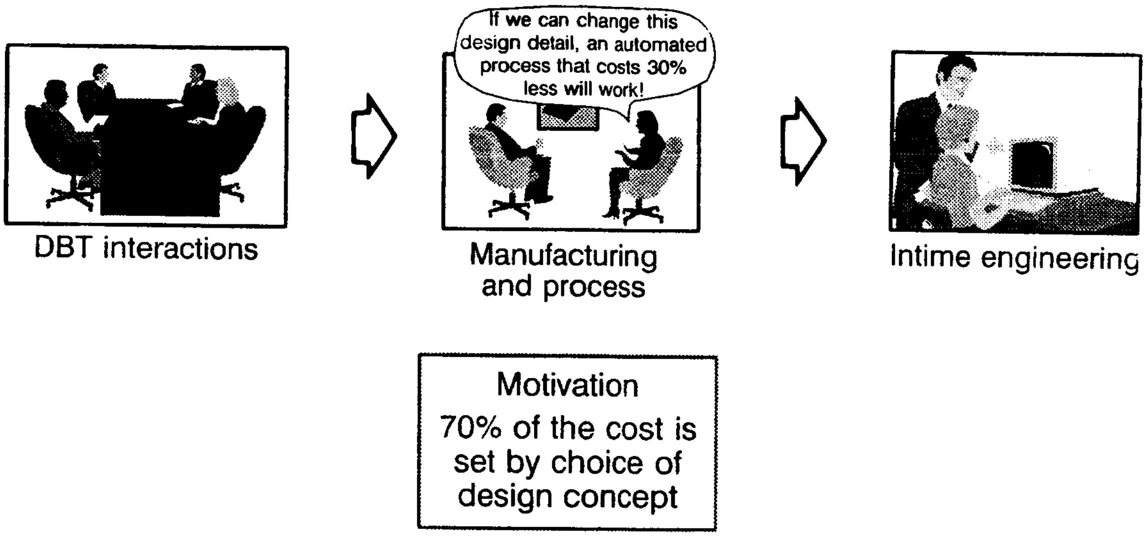



**Figure 3-1: Schematic of DBT Interactions**

Although the idea of a DBT is easily understood, details of formulating the approach can be a difficult task. For example, groundrules used for DBT meetings are generally related to constraints imposed by the needs of a specific application. A long-term research and development program, such as ATCAS, can consider innovative designs and advanced manufacturing technologies, while a near-term hardware program would need to consider concepts having less risk.

As with other teams, successful DBTs need to consider the strengths of individual members when developing their game plan. During initial ATCAS DBT development, several aspects of "team play" were obeyed. Each member was given a voice in deriving the DBT approach and goals. This took considerable time, but helped to stimulate individual interests in the DBT activities and a sense of ownership in accomplishments. Although it is impossible to quantify the effects of team morale on performance, members attended the ATCAS DBT meetings with enthusiasm and completed their supporting work on schedule.

This section of the text will be divided into three subsections. The first documents experiences from initial ATCAS DBT meetings, identifying some of the challenges in establishing a DBT meeting format and team member roles. The second subsection defines families chosen to classify design concepts for transport fuselage structure. The last subsection discusses the three step ATCAS DBT approach.

## 3.1 Initial ATCAS DBT Meetings

Despite the common goal of each team member to strive for "low cost" design concepts, initial ATCAS DBT meetings frequently ended in confusion. These sessions were the first DBT meetings of any type attended by most participants and there was a tendency for discussions to dwell on technical detail. This, coupled with the inherent desire of most team members to present a potentially low-cost idea, led to very long meetings that ended in exhaustion. It became apparent that (1) most issues would have to be resolved outside meetings, and (2) the roles of individual team members needed to be identified. As a result of the first item, it was decided that "action items" would be assigned to individual specialists when stalemates occurred during meetings. The status of unresolved issues were addressed at the start of each subsequent meeting.

The ATCAS design approach requires a large amount of research work by design, manufacturing, cost analysis, structures, and materials personnel to help the DBT (see Section 3.3). Supporting research was required to facilitate concept selection because the innovative designs and advanced manufacturing technologies considered within ATCAS were beyond the scope of existing Boeing databases. As a rule of thumb, 90% of the work on the ATCAS DBT occurred outside meetings. Work statements and schedules were established, enabling team members to understand their support commitments. This resulted in more effective DBT meetings because members would come prepared to resolve issues on the agenda.

Three DBT meeting formats were used for ATCAS. The first format updated schedules and work in progress, including the assignment of new action items. The second, reviewed manufacturing capabilities (Boeing or vendor) and/or tasks completed by DBT members. The first two meeting types occurred most frequently, but attendance by the full DBT was typically not required. Finally, a third meeting format, involving the full DBT, was used for final concept selection. All the technical issues identified for a concept were also reviewed during the final meeting. These technical issues helped to set priorities on technology development and verification tasks.

Based on the complex cost relationships expected for composite transport fuselage, significant contributions from each DBT discipline are needed to achieve desired total cost savings. The initial burden was placed on manufacturing personnel to identify efficient composite processes with potential for cost savings. In answer to this action, a database was generated listing advantages and limitations of known composite fabrication methods. Meanwhile, data obtained from existing cost analysis indicated that cost centers were application specific. Much of the cost was found to be related to selected design concepts, assembly issues, materials, and structural performance criteria. Therefore, it was determined that efficient fabrication methods would only achieve a portion of the desired cost savings.

Each discipline represented in the ATCAS DBT was given a responsibility in pursuit of cost savings. The roles of design, manufacturing, cost analysis, and supporting technologies (e.g., material science and structural mechanics) are listed in Table 3-1. Many of the responsibilities shown in this table are dependent on other groups efforts. Therefore, a schedule that ensures timely completion of work tasks is critical to the success of a DBT.

| Group | Responsibilities |
| --- | --- |
| Design | 1. Organize, run, and document results from DBT meetings.<br>2. Establish the design envelope, configuration constraints, and structural criteria (e.g., damage tolerance) applicable to the concepts under study.<br>3. Create designs and provide formal drawings of fuselage structural concepts to facilitate the development of fabrication and assembly plans. The drawings are intended to ensure consideration of details characteristic of real fuselage structure. |
| Manufacturing | 1. Develop and maintain a database on fabrication and assembly processes. This includes information on process rates, efficiencies, capabilities, and limitations.<br>2. Formulate process and assembly plans best suited for specific design concepts under study.<br>3. Work with supporting technologies to incorporate cost constraints in design tools. |
| Cost Analysis | 1. Project the fabrication and assembly costs of design concepts using detailed manufacturing plans.<br>2. Document the cost centers and assumed technology developments for each concept.<br>3. Develop and calibrate cost models which will expedite future cost estimates. |
| Supporting Tech. | 1. Perform analysis to support concept development.<br>2. Create and maintain a material database. This will include projected costs, properties, advantages, and limitations.<br>3. Develop design tools which enhance the concept selection process.<br>4. Determine the effect of specifications and design/manufacturing criteria on performance versus cost relationships. |

**Table 3-1: Group Responsibilities in Support of DBT Activities**

## 3.2 Definition of Design Families

The design concept chosen for a given application is thought to have a significant effect on costs. For example, some designs add unnecessary costs to the fabrication process by reducing the benefits of potentially low-cost materials or manufacturing processes. Certain design details may even be impossible to fabricate, in which case, costly design changes are required. The cost of such changes become high if they are identified late in the design/manufacturing cycle. A DBT strives to modify concepts early in the design cycle to minimize costs. Any design variations must be made within constraints imposed by the structural configuration (e.g., door and window locations) and systems requirements (e.g., electronics).

Trade studies on the effect of design concept on cost and weight started early in ATCAS with the definition of "Design Families" for fuselage structure. Initially, 30 design concepts were presented by the design group. Following brainstorming by the DBT, the number grew to a total of 159. Many of the characteristics of these designs were similar, allowing them to be classified in families. The families were defined by isolating features with unique manufacturing cost characteristics. The ATCAS manufacturing personnel played the lead role in segregating concepts.

Rationale for defining design families in ATCAS was related to the need for an efficient method of performing cost and weight trade studies. While it was desirable to study as many designs as possible before concept selection, two factors limited the number that could be reasonably evaluated. First, the time used in selecting concepts (designs, materials, and manufacturing processes) was restricted by hardware development and verification schedules. Second, significant amounts of information (detailed designs and manufacturing plans) were required to make accurate cost estimates. Design families are used in ATCAS to minimize the number of concepts considered in the trade study. The selection process starts with a limited number of design evaluations to identify the family with greatest potential for cost and weight savings. A more detailed optimization can then be performed within the selected design family. This global/local design optimization approach is described more fully in Section 3.3.

Eight families of design concepts were defined for ATCAS fuselage structures. Illustrations and a short narrative description that indicates the unique features of each family are given in the following subsections.

### 3.2.1 Family A: Skin-Stringer-Frame (Mechanically Fastened Stringers and Frames)

Family A represents concepts traditionally used in metal fuselage structure (see Figure 3-2). All stiffening and frame elements for Family A are mechanically fastened, as opposed to the bonding included in other families. The increased part count, additional fasteners, complicated assembly tooling, and assembly labor are expected to add significant costs to design concepts in this family. Advantages to Family A may include simplified cure tooling, locational tolerance control, and smaller part size resulting in reduced costs for rejected parts. Based on the current higher material costs, it is unlikely that Family A will be cost-effective for composites when compared to equivalent metals structure.

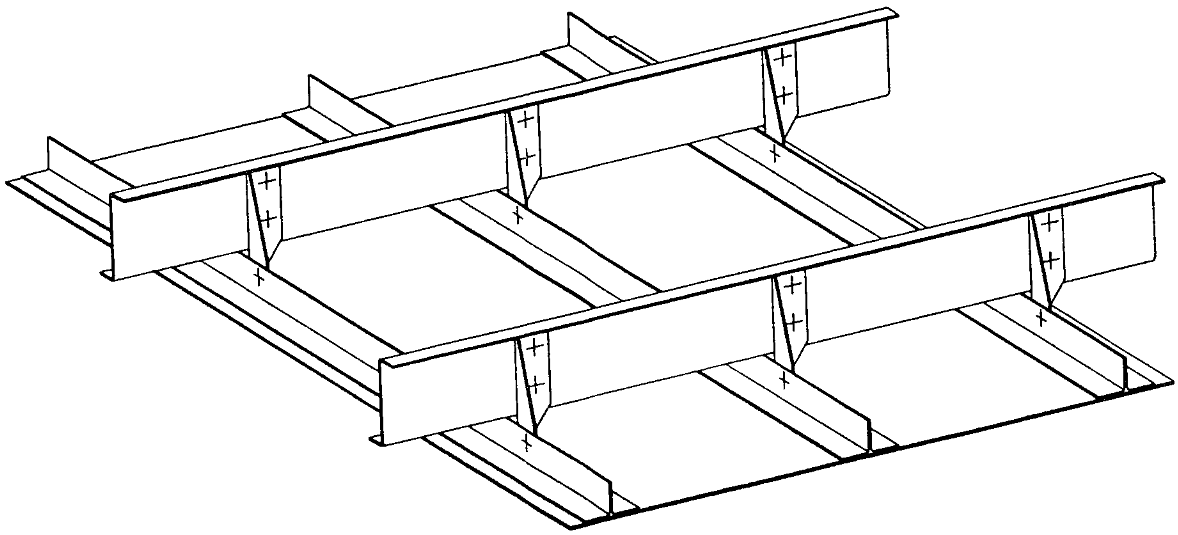


**Figure 3-2: Representative Design Concept from Family A**

### 3.2.2 Family B: Skin-Stringer-Frame (Bonded Stringers)

Family B represents concepts that have received considerable attention for composites (see Figure 3-3). Unlike Family A, the stiffening elements for this family are bonded to the skin reducing part count and assembly costs. Frame elements for Family B remain mechanically attached. Disadvantages of Family B in comparison to Family A include a more complicated cure process and potential loss of locational tolerance control at circumferential splices. The experience base with this design family make it one of the lowest risk families for composites.

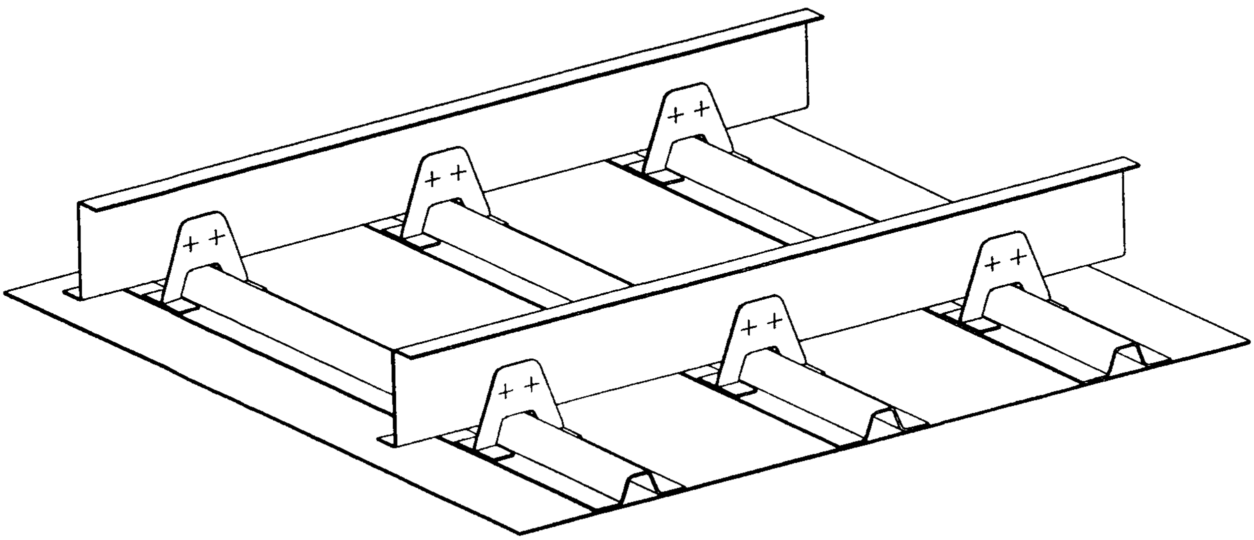


**Figure 3-3: Representative Design Concept from Family B**

### 3.2.3 Family C: Skin-Stringer-Frame (Bonded Stringers and Frames)

Family C represents concepts that trade assembly and fabrication costs (see Figure 3-4). Both stringers and frames are bonded to the skin in this family, greatly reducing part count (e.g., clips or shear ties) and element assembly costs. Disadvantages of Family C in comparison to Families A and B include more tooling and bagging, and potential loss of locational tolerance control at both longitudinal and circumferential splices. The lack of experience base with this design family makes it one of the higher risk families for composites.

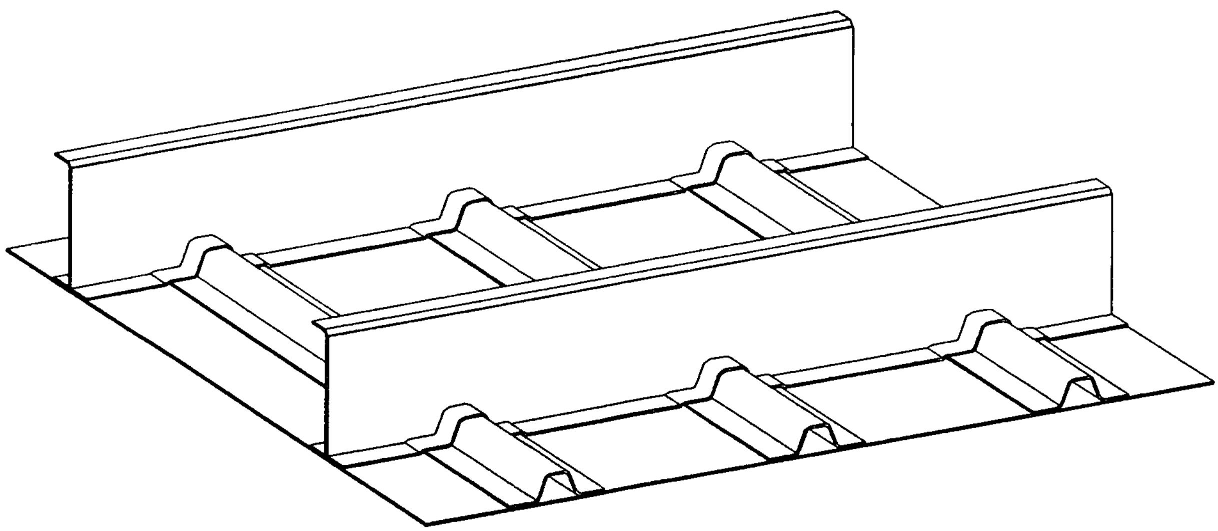


**Figure 3-4: Representative Design Concept from Family C**

### 3.2.4 Family D: Sandwich

Family D represents core (e.g., honeycomb or foam) stiffened structure which, from a manufacturing standpoint, have proven to be cost effective when compared with discretely stiffened skin concepts (see Figure 3-5). The ability to reduce part count, simplify panel geometry/layup, and automate fabrication are some advantages of core stiffened laminates. Disadvantages include difficult panel splices, locational tolerance control for bonded frames, and complicated repair procedures. The experience base with this family is primarily with minimum-gage secondary structures.

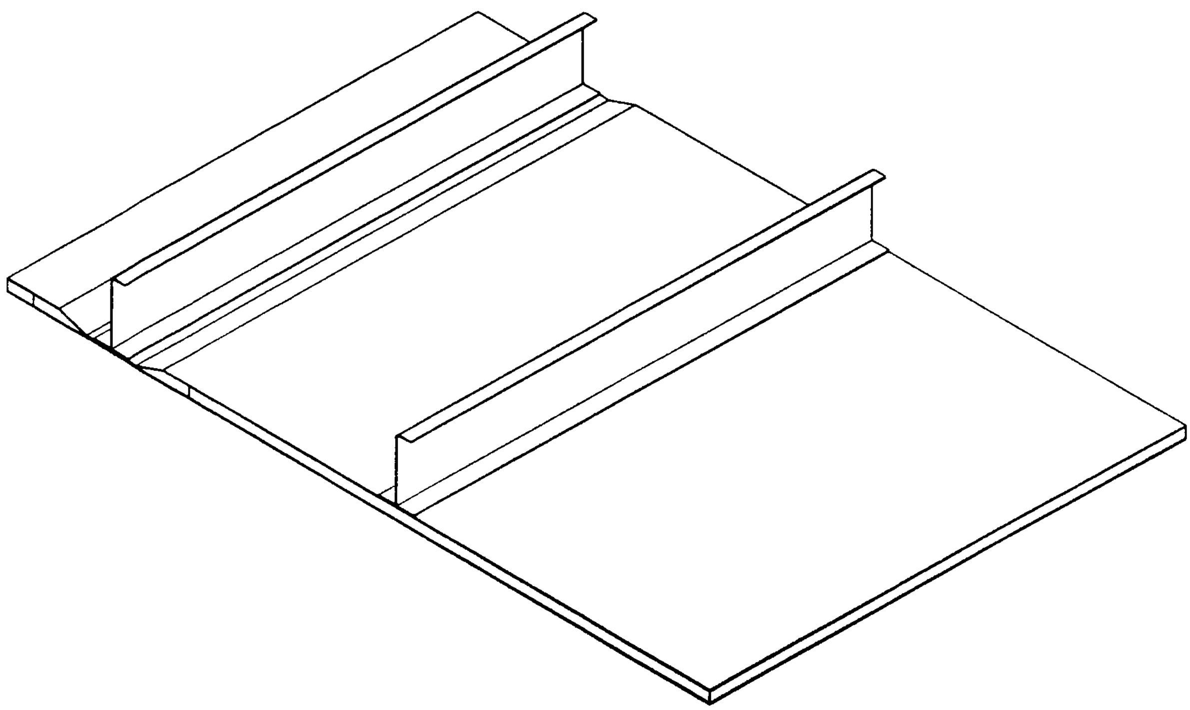


**Figure 3-5: Representative Design Concept from Family D**

### 3.2.5 Family E: Corrugated

Family E represents concepts similar to Family D (sandwich) with the exception that a more involved process is anticipated to layup the corrugations (see Figure 3-6). It is not likely that Family E would be chosen over Family D unless structural requirements (e.g., impact damage resistance) suggest the need for corrugations in lieu of a breakthrough in the honeycomb or foam technology areas. Additional costs for corrugations appear in the areas of cure tooling, mandrel extraction, and laminate inspection. Development of an innovative low-cost fabrication process could make corrugations cost competitive with traditional sandwich core types.

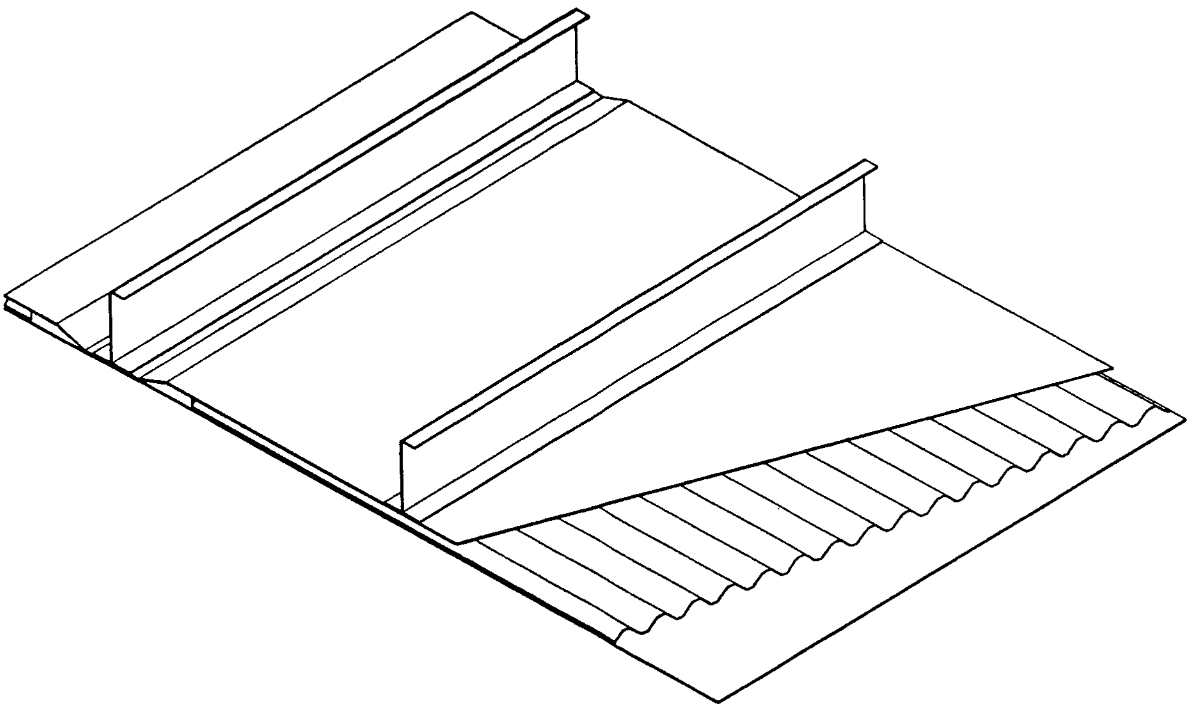


**Figure 3-6: Representative Design Concept from Family E**

### 3.2.6 Family F: Geodesic

Family F represents grid stiffened concepts such as orthogrid or isogrid that are inherently robust because of multiple load paths (see Figure 3-7). Due to a lack of experience with this type of structure in commercial transport applications, the manufacturing advantages and disadvantages are not well understood. Potential advantages are defect insensitivity, reduced part count and lower element assembly costs. Disadvantages appear to be complicated cure tooling and panel splicing difficulties. One significant technical issue affecting the cost of this family is whether or not frames would be required with the grid geometries. The lack of experience base with geodesic structure make it a high risk family.

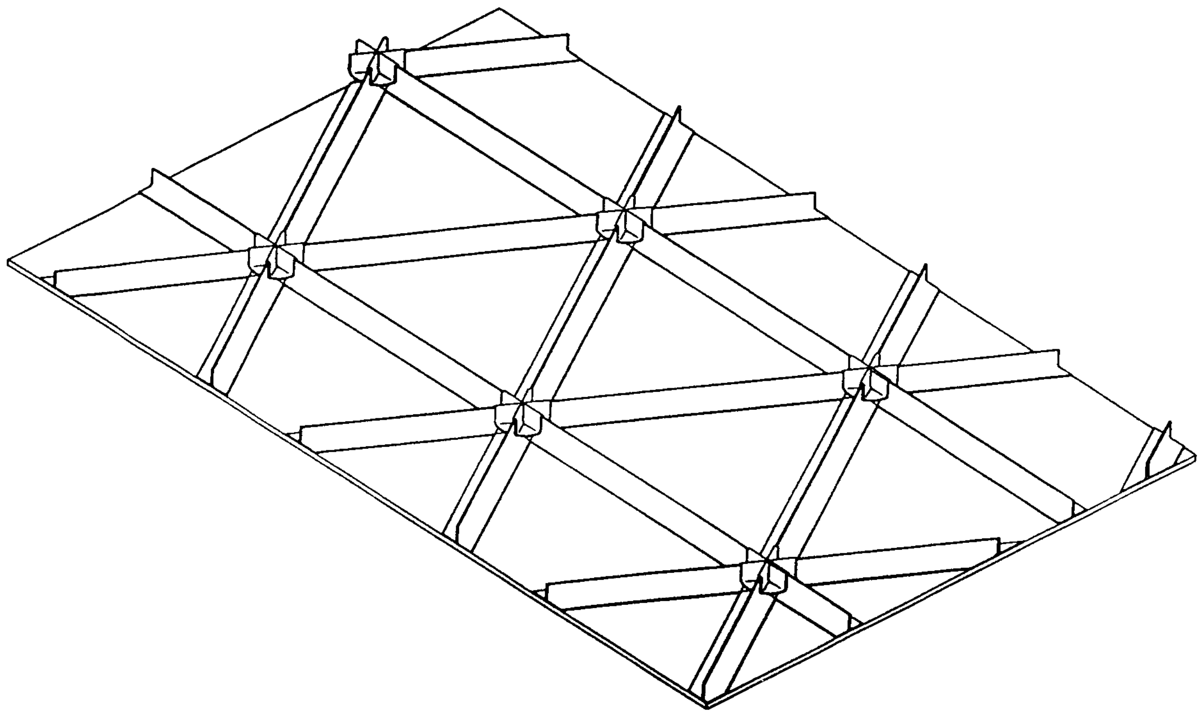


**Figure 3-7: Representative Design Concept from Family F**

### 3.2.7 Family G: Integrally Stiffened Skins

Family G represents a variation of the skin-stringer-frame families, obtained by integrating the skin and stringer flange (see Figure 3-8). The integral stringer flange area may be beneficial for some structural applications. Although many of the advantages and disadvantages of Family G are similar to those of Families B and C, the potential fabrication methods are sufficiently different to warrant the separate classification. An innovative fabrication process using unique tooling concepts may be very cost effective for some designs within Family G.

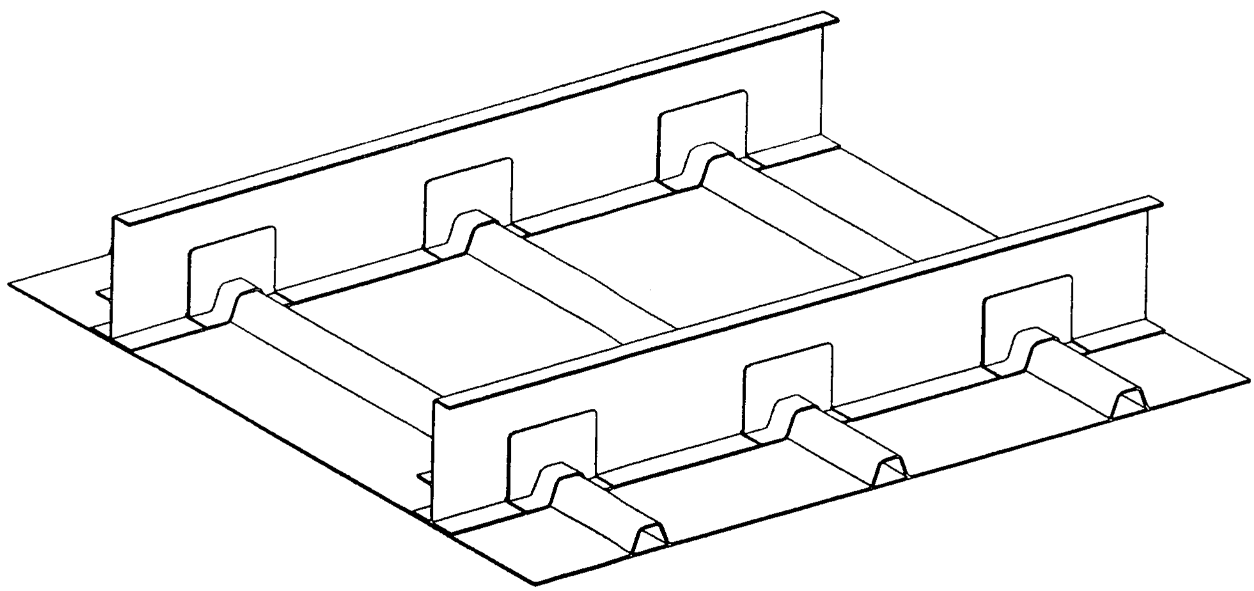


**Figure 3-8: Representative Design Concept from Family G**

### 3.2.8 Family H: Continuous 360°

Family H represents a variation to any of the other families in the form of a 360°, one piece shell, concept that eliminates longitudinal splices (see Figure 3-9). The one piece shell carries the obvious advantage of further part count reductions and simplified assembly tooling. Complications are likely to occur in the areas of cure tooling, control of aerodynamic surface finish, and mating of one cured shell to another. Development of a 360° concept can take place only after the complexities of the window belt, passenger door and keel beam area are better understood. Shell fabrication will require the application of compatible processes which can accommodate the unique requirements of those areas.

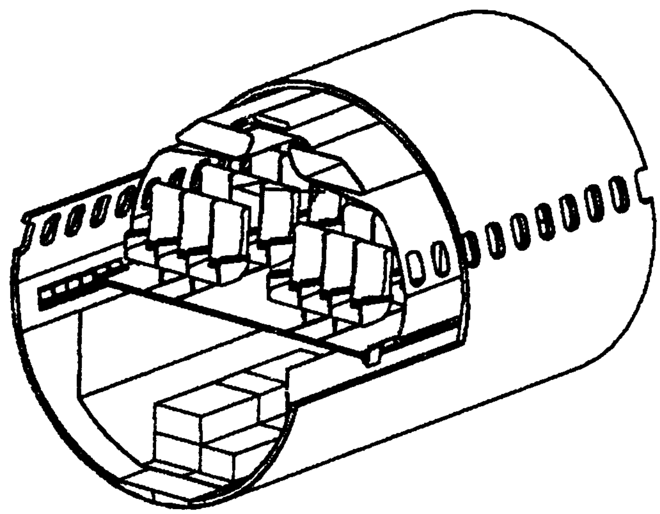


Figure 3-9: Representative Design Concept from Family H

## 3.3 Three Step ATCAS DBT Approach

The ATCAS program considers design details in order to select concepts that will lead to cost savings for the assembled structure. Design of individual elements (e.g., stiffened skins, frames, splices, clips, and attachments) can have a significant effect on both fabrication and assembly costs. A design that includes details of the attachment of each element is also critical, due to numerous interactions. For example, a concept from Family H (Continuous-360°) may appear to greatly reduce the outer shell fabrication and assembly costs; however, the remaining assembly costs due to adding design details (e.g., stiffening elements, window frames, door structure, and floor structure) may eliminate any potential cost advantage.

Hardware design efforts are normally constrained by time. As discussed earlier, all DBT members collaborated to develop a three step design approach suitable for the ATCAS program. One highlight of this approach is allocating DBT time early in the design cycle to include structural details in cost estimates. As a result, more complete cost estimates are available to evaluate concepts before committing to hardware development and verification tasks. Although this adds time to the design process, the total time needed to apply the three step approach can be constrained to meet a specific program schedule. For example, time can be shortened by reducing the number of design families considered in Step #2 and/or the extent of element optimization in Step #3.

### 3.3.1 Step #1: Baseline Concept Selection

The first step in the ATCAS design process, is the selection of a "baseline" concept (i.e., a design family and associated manufacturing process) for each fuselage area. Baseline concepts are selected without the aid of detailed cost and weight estimates, and are therefore, considered a conceptual starting point. Design personnel support this DBT effort with conceptual sketches, while manufacturing personnel project cost-effective fabrication and assembly processes. A limited amount of mechanics and materials support is also used to estimate the performance of baseline structures. During the formulation of baseline concepts, features are altered whenever they are judged to add costs or lead to unacceptable performance.

The selected baseline concepts are those judged to have the greatest potential for cost savings, combined with an acceptable risk. The risk relates to projected achievements in manufacturing and structures technology during the length of the ATCAS contract. In addition to selecting design concepts for more detailed study, the ATCAS baseline design step identifies critical manufacturing and performance issues that are expected to drive the design.

Baseline concepts provide the starting point for other technology tasks in ATCAS. Cost and weight trade studies, which constitute the second design step, initially consider the design details and assembly issues of the baseline concept. The baseline concepts will also be the first manufacturing demonstration panels built for each quadrant. Finally, critical mechanics and materials issues associated with baseline concepts trigger initial supporting technology developments. Section 4 of this document will discuss the baseline concepts selected for the ATCAS program.

### 3.3.2 Step #2: Global Optimization

The objective of this design step is to use detailed drawings (i.e., integration of all elements, including panel splices) and cost analysis to compare the baseline concepts to other potentially low-cost concepts and the aluminum counterpart. This step may be termed a "global optimization" effort in which sufficient detail (e.g., preliminary design values) is considered to determine significant cost differences between the concepts studied. The scheduled order of global optimization studies for different areas of the fuselage in ATCAS is crown, keel, and window belt. The completed efforts with the former are documented in Section 5 of this report. The results for other areas are scheduled to be completed and documented by the end of Phase A (October, 1991).

Results from global optimization studies include:

1. Quantitative ranking of design families studied.
2. Identification of cost centers for higher ranking concepts.
3. Defined and prioritized list of technical/economic issues and barriers.
4. Identification of parameters that control concept response.

These results initiate final development and verification tasks. Cost data justifies the selection of a family of concepts for the more detailed studies which attack cost centers (the third design step). Manufacturing and supporting technology activities are also updated to address specific issues related to the selected concepts.

Design efforts in global optimization start with identification of the design envelope including panel size, loads, configuration constraints, and performance criteria. Work then begins on detailed design layouts of the baseline concept. Supporting technologies provide initial design values (e.g., preliminary elastic moduli and allowable strengths) to assist panel and element sizing efforts. Although the best available design values are used for initial sizing, the accuracy of performance predictions during this design step is not critical. Approximate sizes and structurally sound load paths are the primary concern. The key to global optimization is to estimate cost and weight with enough accuracy to justify more detailed studies with a design concept. All design elements and assembly steps affecting cost are considered in global optimization; however, concerns about small differences in part size needed for adequate performance are left for local optimization studies, when a more complete database becomes available.

The DBT also selects a limited number of alternative concepts from design families for cost and weight comparisons with the baseline concept. In order to promote a fair comparison, each alternative concept evaluated must also have a corresponding detailed design layout. As with baseline concepts, additional DBT selections are made based on structural requirements and the potential for manufacturing cost savings.

The completed design layouts contain information needed to generate detailed manufacturing plans. Process and assembly plans are developed in parallel with DBT efforts on specific design family concepts. The plans provide the necessary information for cost evaluation of design concepts during global optimization. The cost modeling work helps to identify critical manufacturing cost centers for process development efforts. Therefore, assembly and process plans, initially produced to support the DBT activities, eventually yield data to guide manufacturing process development in directions that have the greatest impact on costs. This interaction is shown in Figure 3-10 as a flow diagram.

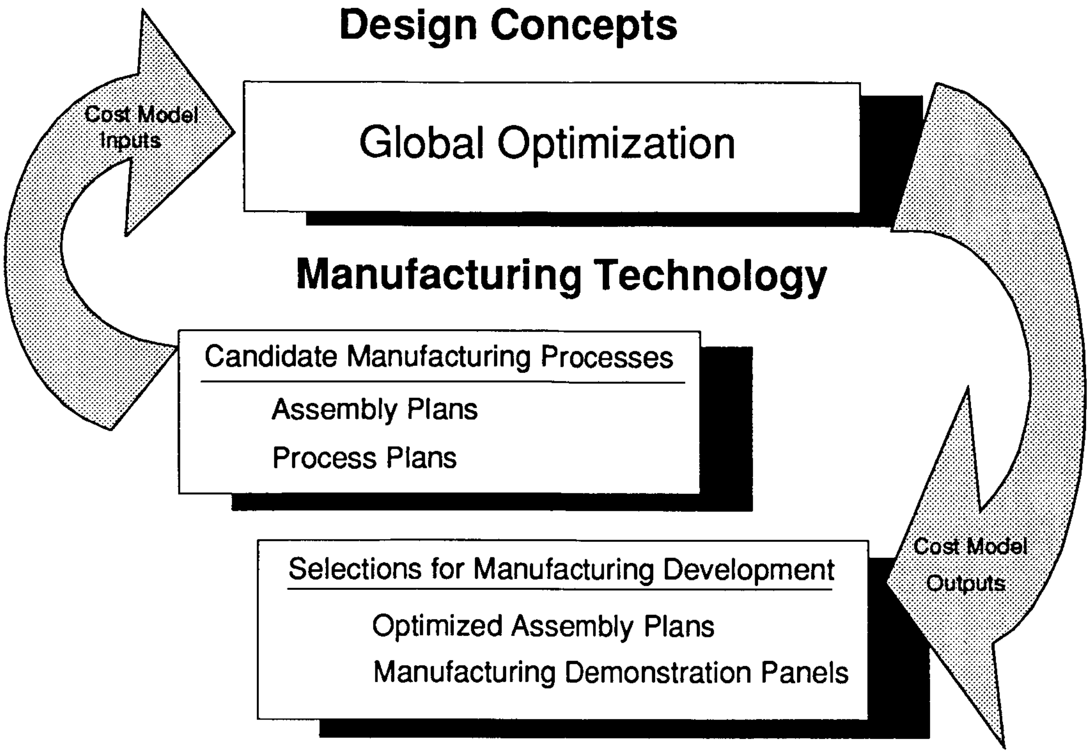



**Figure 3-10: Interactions Between Manufacturing Development and DBT Efforts**

A cost estimate is the next stage of global optimization. As a previous study points out (Ref. 3-1), cost predictions are strongly dependent on the accuracy of inputs. The manufacturing process and assembly plans are used to develop cost estimates. They define the tooling and recurring material requirements for each process. In-house historical data and vendor-supplied estimates are used to define machine capabilities, process limits, and costs of materials and individual operations. Process variables, such as learning curves, shop variances, and labor standards, are also generated from historical and vendor-supplied data. Detailed costs for each operation are then generated, and summed to provide various levels of cost visibility.

The detailed cost estimates are used to calibrate the complexity factors used in a parametric cost model (G. E. PRICE, Ref. 3-2) for each fabrication and assembly process. During global optimization, a wide variety of processes are evaluated on a variety of structural-members types. As sufficient calibration for a specific process is obtained, the parametric approach replaces the detailed analysis for that process.

Several ground rules were used for cost estimates developed in ATCAS. Some of these are based on the recommendations of participants at NASA Advanced Composite Technology (ACT) cost workshops. A description of the ground rules are given in Table 3-2.

General: The cost estimate used the detail definitions produced by the DBT, and further discussions between manufacturing engineers and the estimating group. An automated factory was assumed for definition of equipment and tooling. Focus was on the reduction of part handling and the combination of operations where beneficial.

Recurring:

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.

Nonrecurring:

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 costs are not included.
5. Nonrecurring labor wrap rate is assumed to be $75/hr.

**Table 3-2: Ground Rules for ATCAS Cost Estimates**

As discussed earlier, several design concepts are considered during the course of global optimization. Due to the detailed information required for cost estimating, the number of concepts evaluated is limited by the available time. The ATCAS crown global optimization considered six design concepts, two from each of three families, over a period of six months (see Section 5 of this report). More complicated designs such as a keel or side panel may not permit as many alternative concepts when constrained by similar time periods.

Several secondary advantages to the global optimization design step have been noted to date during applications with crown panels in ATCAS. First, an inherent system to check the accuracy of cost and weight estimates occurs when comparing results from several designs. For example, disparities in results become evident when attempting to make sense of the differences between designs. This is particularly helpful for the detailed cost estimates which involve tedious accounting tasks where errors are possible during data entry and plotting. The consideration of more than one design for each family has also been found useful when interpreting a families' cost sensitivity to design, material, and process variables. The resulting global optimized decision to concentrate on a particular family during the final design step is based on both (1) concept cost and weight estimates, and (2) potential for further reducing costs as indicated by trading variables within a family.

The complete approach taken in global optimization is illustrated schematically in Figure 3-11. In summary, the DBT selects concepts that are designed in sufficient detail to develop manufacturing plans and, subsequently, cost and weight estimates. A comparison of costs for alternate concepts will form the basis for selecting a design family best suited for local optimization. Even before local optimization, variables (e.g., frame processing methods) can be traded between designs to judge the family with greatest potential for low cost and weight. This additional level of interpretation was found critical for the crown study described in Section 5 of this report where the global optimization results did not delineate families to the extent idealized in Figure 3-11.

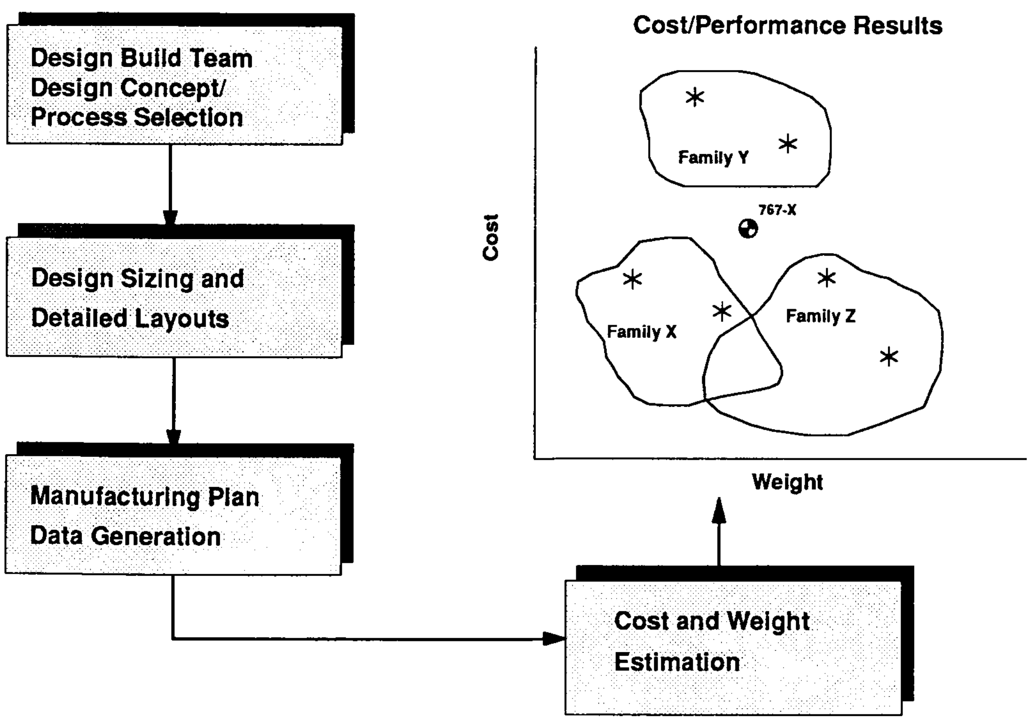



**Figure 3-11: Global Optimization Design Step**

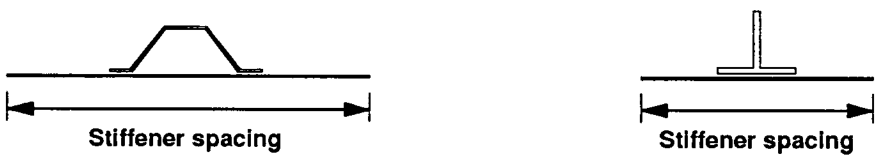
### 3.3.3 Step #3: Local Optimization

The third and final step in the ATCAS DBT approach uses a high ranking concept selected from global optimization studies in a concentrated effort to optimize element design. This may be termed a local optimization of design family elements (e.g., skin, stiffener, frame, etc.) that considers how changes to the design impact cost centers in a global sense (i.e., the assembled structure). Typical variables for local optimization include those considered by designers in configuration development (e.g., skin layup & thickness, stiffener geometry, material type, and manufacturing process).

The results from global optimization trade studies (Step #2) are used to establish cost constraints on local element optimization. When considering assembled structure, the total cost trades may be complex. Figure 3-12 shows an example of complex cost trades that became apparent in ATCAS studies involving two different stiffener geometries.

**Stiffener Variable Design Cost Trade Study**

- **Design is a function of loading levels**
- **Hat stiffeners can be spaced farther apart (fewer needed)**
- **Hat stiffeners are more complex to splice (more expensive)**
- **Hat stiffeners have less complex tooling (less expensive)**




- **A trade study on the interactions of the following must be made:**
  - **cost of manufacturing the individual stiffener**
  - **the number of stiffeners required**
  - **cost of splicing the ends of the stiffener**
  - **cost of assembling the skin and stiffeners**

**Figure 3-12: Examples of Assembly and Process Cost Constraints Discussed in Crown DBT Meetings**

Ideally, software can be developed to aid the local optimization process. Such engineering tools must consider multiple load cases, damage scenarios, and numerous structural and cost constraints characteristic of real world applications with composites. These conditions suggest an optimization algorithm capable of handling discontinuous functions. One such method under investigation in ATCAS is a sequential random search technique (Ref. 3-3). This technique is an improvement over more conventional optimization algorithms that use local derivative functions to locate the minimum. For example, derivative based methods may converge to an apparent minimum rather than the absolute minimum. Because the random search technique does not rely on local derivatives, discontinuous functions common in composite structures (e.g., discrete ply thicknesses and stacking sequences) can be used in the formulation of optimization constraints.

Several other activities are scheduled to support the structural design efforts during local optimization in the ATCAS program. Manufacturing process and assembly trials are used to explore new technologies which could help to reduce the projected cost centers from global optimization. In addition, the potential for reducing manufacturing costs with automation and process efficiency are explored through industrial engineering plans of enhanced machine design and factory layout, respectively. Experimental data bases on the mechanical performance of alternative, low-cost materials are also generated to incorporate them in local design sizing exercises.

An illustration of the local optimization process appears in Figure 3-13. In summary, the final design step involves comprehensive manufacturing and supporting technology studies by the DBT to further reduce the cost and weight of a globally optimized design family. Detailed cost analysis of the locally optimized concept will help to validate the final selection.

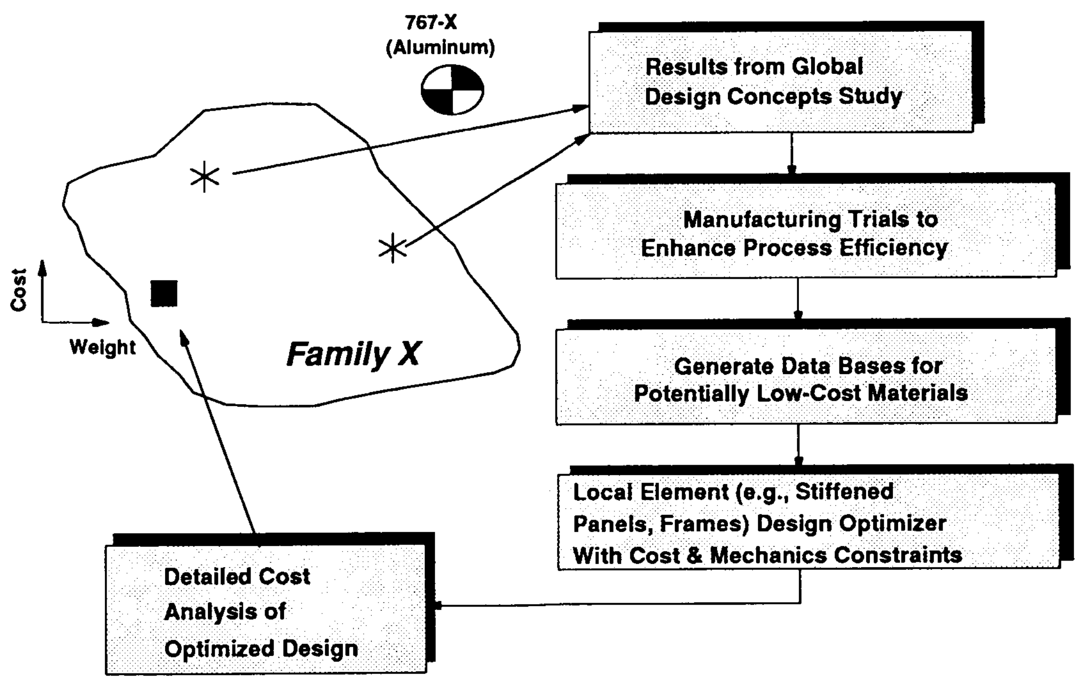



**Figure 3-13: Local Optimization Design Step**

At the time of report preparation, the ATCAS program had just initiated local optimization with crown panels. As a result, experience-based recommendations on applications of Step #3 in the design process can not be made at this time. However, additional cost and weight savings potential were apparent following a review of results from the globally optimized crown studies (see Section 5). For example, visibility of the cost centers for a concept precipitates the DBT task of minimizing cost in more detailed studies.

# 4.0 ATCAS BASELINE CONCEPTS

Baseline concept selection in ATCAS occurred over a period of six months. Concept development was initiated by a DBT subcommittee consisting of four members: (1) a designer with fuselage experience, (2) structures/materials analyst, (3) manufacturing process specialist, and (4) assembly advisor. Each member of the subcommittee also consulted other expertise as deemed necessary. In addition, each baseline concept proposed by the subcommittee was reviewed with the full ATCAS DBT prior to final selection. This helped to complete a list of major economic and technical issues associated with each concept.

Baseline concept selection constituted the starting point in ATCAS design studies for keel and window belt (side) panels. The scheduled completion date for baseline concept selection coincided with the end of global optimization for crown panels. This allowed the keel and window belt panel baseline decisions to benefit from cost and weight trade studies conducted for crown panels.

## 4.1 Quadrant Panel Definition

The number of panels that comprise a section of the fuselage was limited to four "quadrants" in ATCAS. The crown, right-side, keel, and left-side quadrants are illustrated in Figure 4-1. Quadrants were used in ATCAS to reduce manufacturing costs in two ways. First, large quadrant panels minimize the number of longitudinal panel splices. Second, the baseline fabrication method chosen for panel skins (advanced tow placement) is suitable for efficient batch processing of quadrant segments.

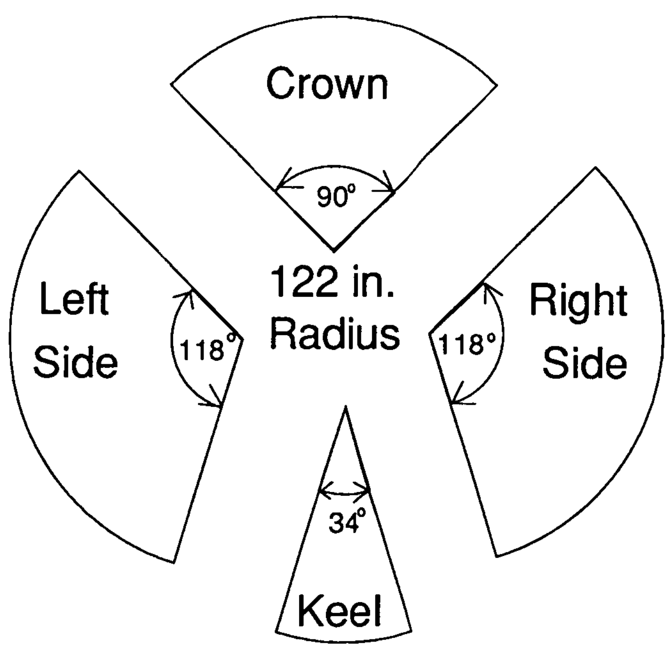



**Figure 4-1: Exploded Circumferential View of Fuselage Quadrants. Note That Each Quadrant Panel Is 374 In. Long**

Figure 4-1 shows that the arc lengths of individual fuselage quadrants are unequal. This was done to allow batch processing of individual quadrants. Crown, keel and side quadrants are produced in different batches due to distinctly different laminate layup and thickness tailoring requirements in each quadrant (e.g., increased thickness near doors). Skin thickness compatibility between adjacent segments must be maintained when tow placing multiple skin panels around the circumference of a winding mandrel.

Figure 4-2 illustrates the number of manufacturing segments produced in a batch process for each quadrant of the fuselage. Note that the figure idealizes the mandrel cross-section as circular. Actual mandrel shape includes a joggle at the edges of each quadrant panel (e.g., quarter points for crown panels) to allow for the geometry of longitudinal splices and cutting waste.

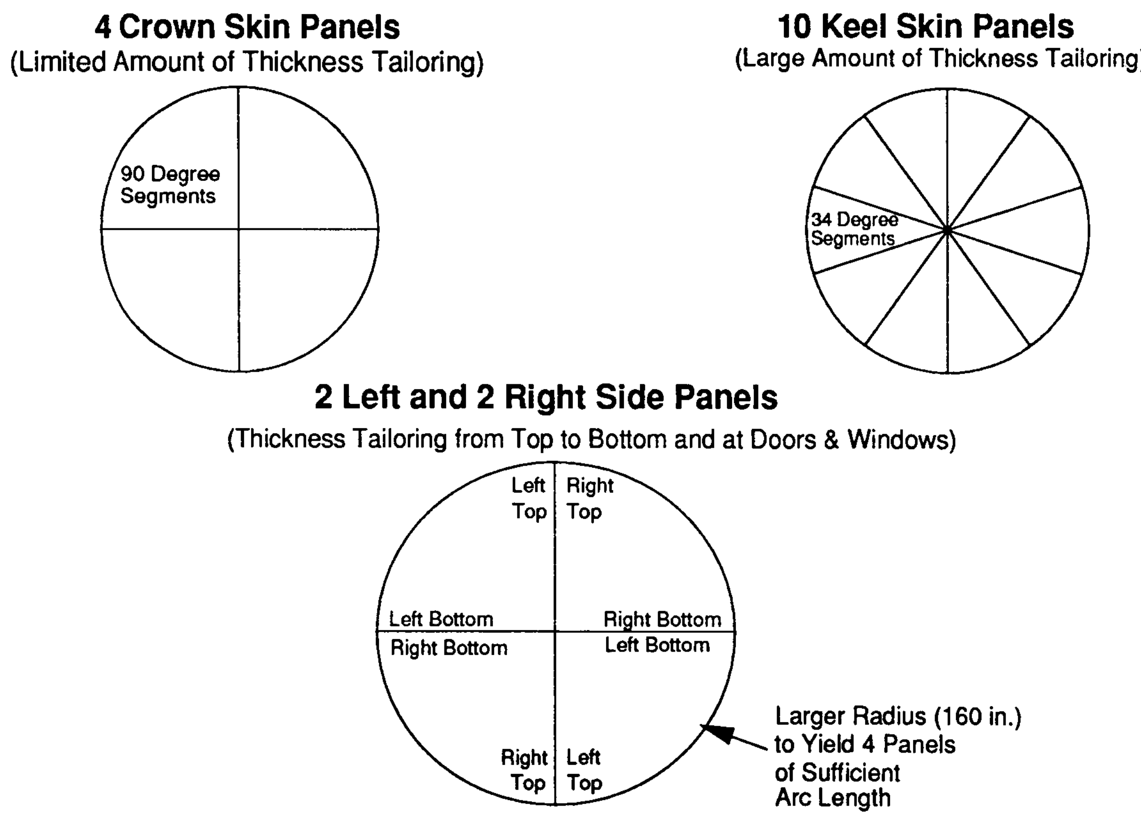



**Figure 4-2: Circumferential View of Advanced Tow Placed Manufacturing Segments**

The limited amount of thickness tailoring required in the crown quadrant results in the highest machine layup efficiency when producing crown baseline skins. Each tow placement wind for the crown matches right to left edges and yields a batch of four uncured laminated skin panels. This technique required design constraints that forced the laminate configurations (thickness tailoring, layup) along the left and right edges of the panels to be identical.

Keel quadrants are relatively small due to a configuration constraint imposed by a cargo door on the right side. Each tow placement wind for the keel quadrant matches right to left edges and yields a batch of ten uncured laminated skin panels. The considerable amount of thickness tailoring required for load redistribution in the keel panel reduces machine efficiency; however, some of this will be offset by the large number of shipsets per wind. As with the crown, a design constraint will be imposed on the keel quadrant to ensure right-left symmetry and, hence, compatibility of the tow placed manufacturing segments.

Two shipsets of skins for right and left side quadrants are wound on the same mandrel during each tow placement wind. An even number of panels are required, as explained in the following paragraph. As a result, the mandrel for producing side panels will be somewhat larger than that used for keel or crown quadrants in order to produce a total of four panels of sufficient arc length in a single wind. Thickness tailoring and the small number of shipsets per wind for side panels are expected to impact the manufacturing costs.

As shown in Figure 4-2, both side quadrants are wound on the same mandrel by matching "Left Top" to "Right Top" and "Right Bottom" to "Left Bottom". This will be implemented by constraining side panel designs to have compatible laminate layups and thicknesses at the two top longitudinal splice locations and, similarly, concurrent laminate configurations at the two bottom splices. Compatibility will force right and left panel layups at longitudinal splices that differ only in the sign of angle plies. Due to differences in right and left door locations, panel laminate configurations away from panel edges are not constrained to be identical on the two sides.

Additional motivation for combining right and left baseline panels in the same wind relates to large weight and cost penalties for tow placing them separately. For example, a heavy panel would result when enforcing laminate thickness and layup compatibilities between top and bottom edges of the same side. In order to match top or bottom edges of the same side during winding (e.g., "Left Top" to "Left Top"), laminate variables would need to be constrained such that a forward-to-aft symmetry existed. This would be weight inefficient considering door design details and forward-to-aft variations in load. With materials a significant cost center, weight efficiency is often directly related to cost savings for a particular material.

## 4.2 Baseline Concept Descriptions

The most critical fabrication and assembly details (e.g., doors and keel beam splice) were considered during baseline concept selection. This led to design family selections having features that are compatible with design details and, hence, reflect cost and weight savings of the real fuselage. The same was done for the baseline manufacturing processes which were selected to maintain efficiency for the most costly design features. Finally, designs and processes were chosen with a strong potential to be demonstrated via manufacturing large fuselage subcomponents by 1995.

### 4.2.1 Crown

As mentioned earlier, schedules allowed crown baseline selection to occur following global optimization. Therefore, detailed cost and weight estimates substantiated the choice. Note that Section 5 of this report documents these crown studies.

A design concept from Family C (skin/stringer/frame with bonded stringers and frames) was chosen as the crown baseline. Figure 4-3 illustrates a representative area of the crown baseline quadrant. Frames are mouse-holed to avoid a complex bonding detail with the hat shaped stringers.

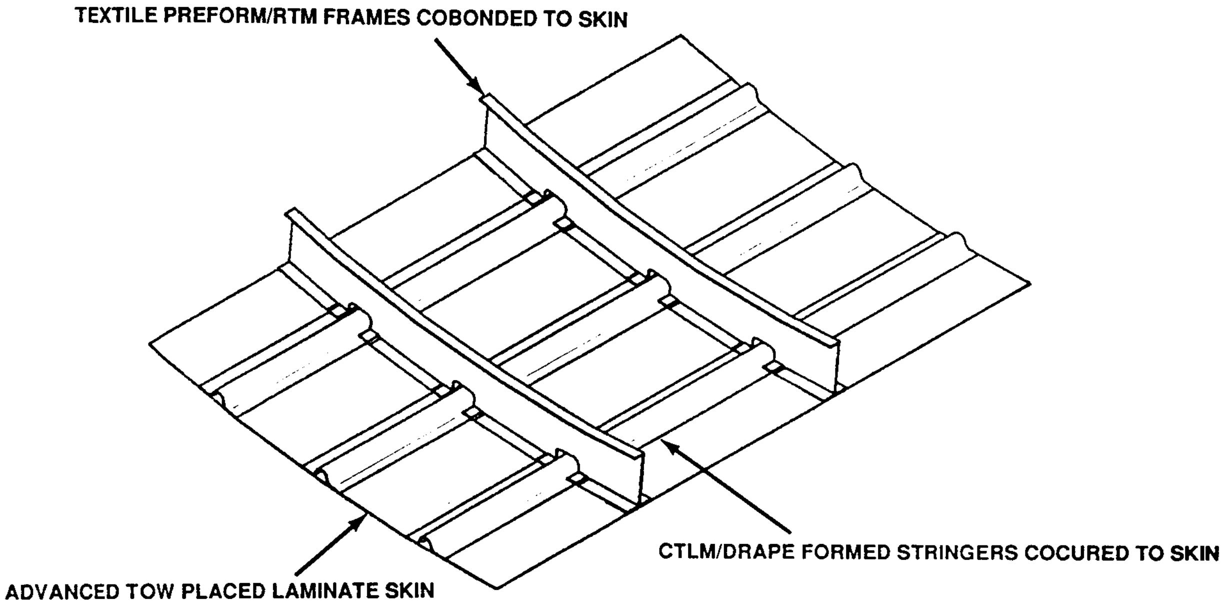



**Figure 4-3: Crown Baseline Design Concept and Fabrication Processes**

Skin panels constitute the bulk of crown quadrant weight. Computer automated advanced tow placement will be used to manufacture the skins. Cost results for crown panels studied in global optimization indicated that the labor for tow placing quadrant laminates was less than 20% of the material cost. Additional cost advantages include the projection that prepreg tow will have significantly lower cost than prepreg tape in future years.

Additional crown baseline elements include cocured hat stringers and cobonded J frames. A contoured tape lamination machine (CTLM) will be used for stringer ply layup. A hot drape forming process will then be used to shape the hat stringers. Textile preforms (2-D) in a J-shape will be resin transfer molded (RTM) to form curved frames. The frames will have sufficient thickness to account for stress concentrations at the mouse-holes. Finally, the precured frames will be cobonded to the uncured skin and stringers to complete fabrication of full crown quadrant segments (≈ 192 in. by 374 in.). Additional features of the manufacturing process will appear in Section 4.3 of this report.

### 4.2.2 Window Belt (Side)

A variation of design concepts from Family C (skin/stringer/frame with bonded stringers and frames) was chosen as the side panel baseline. The variation includes door and window design details. Figure 4-4 illustrates the window belt area of the side panel baseline. A skin/stringer/frame design family was chosen to facilitate design details at

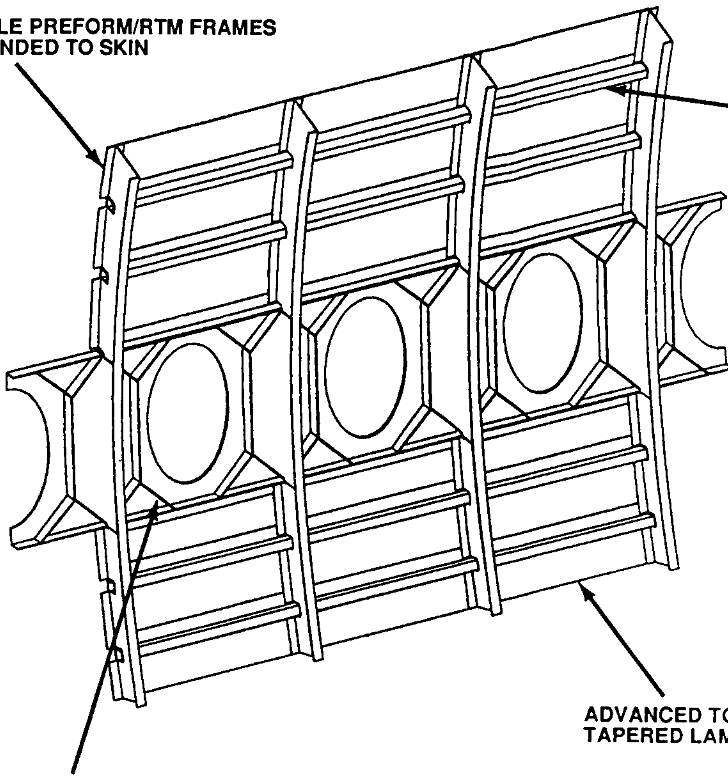



**Figure 4-4: Side Baseline Design Concept and Fabrication Processes Near the Window Belt**

Skins for both side quadrants will also be produced in a batch tow placement process as described in Section 4.1. The skin thickness of side quadrants is close to minimum gage approaching the lower edge of the crown and relatively thick near the upper edge of the keel. Increased skin gages also occur locally near doors and windows. Automated batch processing and the significant amounts of ply tailoring possible with the advanced tow placement method led to its selection for the side quadrant.

Side baseline elements include cocured stringers and cobonded frames. The stringer and curved frame geometries will be established after more comprehensive design studies in global/local optimization. Baseline processes and material forms for both these elements are the same as described for the crown. The window frame inserts will be textile preforms fabricated in an RTM process. Finally, the precured frames (circumferential and window belt) will be cobonded to the uncured skin and stringers to complete fabrication of full side quadrant segments (each side ≈ 251 in. by 374 in.).

Circumferential frames are mechanically attached to window belt frame inserts at their intersection. Additional features of the manufacturing process will appear in Section 4.3.

### 4.2.3 Keel

A variation of design concepts from Family D (sandwich) was chosen as the keel baseline. The variation includes a thick laminated plate to replace (panelize) the discrete keel beam chords. The thick plate gradually transitions into a sandwich panel as axial compression loads are distributed into the monocoque aft of the section splice. The sandwich face sheets have tapered thickness in the transition zone. Figure 4-5 shows the heavily loaded end of the keel panel baseline near the section splice.

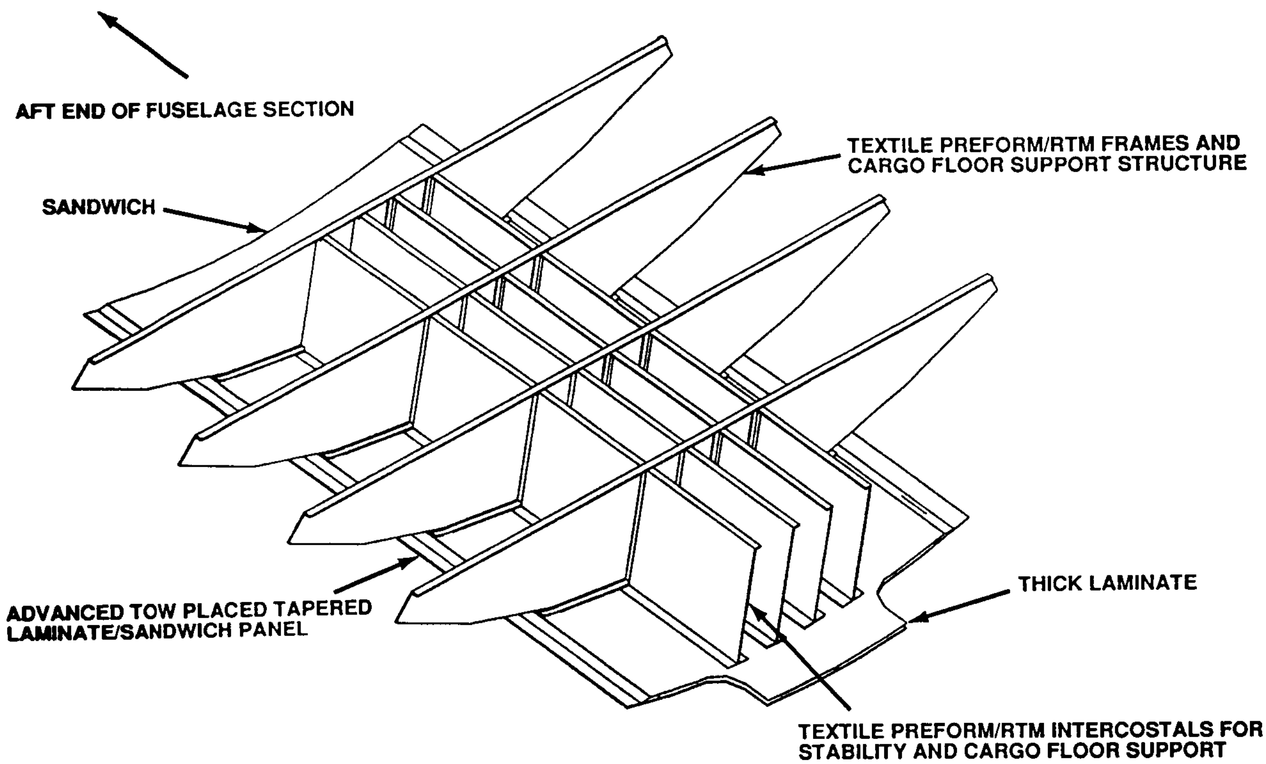



**Figure 4-5: Keel Baseline Design Concept and Fabrication Processes**

This innovative panelized concept was chosen for the keel quadrant baseline for several reasons. First, it avoids problems in fabricating and splicing two large composite keel chord members with rectangular cross-sections on the order of 6 in. by 2 in. For example, large fastener hole diameters needed to mechanically splice discrete composite chord members of this size would cause a significant knockdown on the allowable strength. The panelized concept simplifies this problem to some extent. The blended thick laminate/sandwich construction also yields a constant gage panel that avoids problems in attaching frames and other floor support structure to the keel panel (e.g., bonded frame shear ties would be difficult for a more traditional skin/stringer design having skins with considerable thickness taper).

Facesheets for the keel panel will also be produced in a batch tow placement process as previously described in Section 4.1. Again, automated batch processing and significant amounts of ply tailoring possible with the advanced tow placement method led to its selection for the keel quadrant. The sandwich core will be machined with a constant taper to keep the keel panel at a constant gage as facesheet plies are dropped. The material form used for core will be selected during global/local optimization.

Keel baseline elements include intercostals and full-depth frames. Both these elements serve two purposes; (1) overall panel stability and (2) cargo floor support. Note that intercostals are discontinuous at the frames. The intercostal and frame geometries will be established after more comprehensive design studies in global/local optimization. Textile preforms with an RTM process will be used for both. The frames and intercostals will be mechanically attached to shear-tied blade elements on the fully cured keel panel. These blade elements will be cobonded to the keel panel during cure. Fully assembled keel quadrant segments will each be small in comparison to side and crown panels (≈ 72 in. by 374 in.). Additional features of the manufacturing process will appear in Section 4.3.

## 4.3 Projected Manufacturing Steps for Baseline Fuselage Section

As previously indicated, the majority of costs to fabricate a composite fuselage are affected by early design/manufacturing decisions. A DBT can be used to make cost-effective decisions and avoid downstream modifications. Past experience has shown that design or fabrication modifications escalate costs. A robust design/manufacturing approach can be used to minimize cost sensitivity.

The manufacturing/assembly plans for baseline design concepts use extensive automation and quality control measures within each work station to satisfy the needs for a low-cost assembled structure. Unique large panel configurations require a factory flow process that minimizes the amount of material handling. The factory is divided into seven major work stations (see Table 4-1 and Figure 4-6). The common goal of each work station is to complete a task and minimize efforts required at subsequent work stations.

| | Work Station | Activity |
|---|---|---|
| 1. | Tow Placement Center | Skin fabrication |
| 2. | RTM / Textile Center | Frames, window belt, quadrant splice straps fabrication |
| 3. | Automated Tape Layup and Drape Forming Center | Stringer fabrication |
| 4. | Quadrant Subassembly | Frame/stringer/skin assembly and preparation for cure/cobonding |
| 5. | Cure/Cobonding | Quadrant panel fabrication |
| 6. | Inspection | NDI for detail parts and cured panel |
| 7. | Final Assembly | Longitudinal and circumferential splices |

**Table 4-1: Factory Work Station Activities**

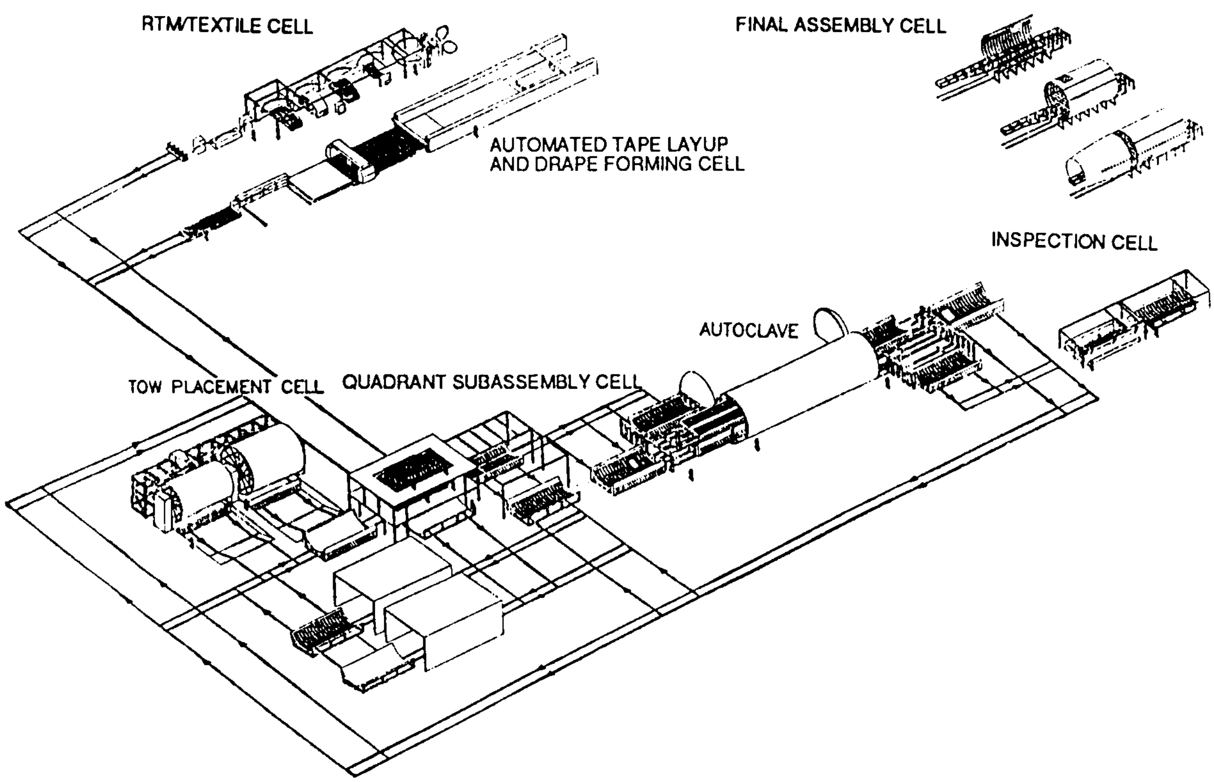



**Figure 4-6: Full Factory Layout**

To eliminate manual factory process flow problems, automated guided vehicle (AGV) robots will be used to deliver materials and parts to the requesting work station. Since work stations are centered around a particular task or process, quality control is maintained by Statistical Process Control techniques. All precured parts are inspected prior to subassembly. Automation must be used to decrease the part in-line inspection.

### 4.3.1 Tow Placement Center

The tow placement work station is a flexible robotic work cell for fabricating the crown, side, and keel skins (see Figure 4-7). The output for a single head ranges from 10-50 lbs./hr., depending on the design requirements. The output for the crown skin of Design C2 (see Section 5) was found to be approximately 20 lbs./hr. for a finished uncured skin, which includes down time and ply tailoring. Although the tow placement head has been demonstrated for a single head dispenser, additional heads that are single or multiple task oriented may be implemented with the proper software development. Since multiple head operations are interdependent, downtime or slower head operation for one head decreases the payout efficiency of the other heads. An alternative method to increase the payout rate is to increase the width of the placement head, and therefore the band that is placed in a single pass.

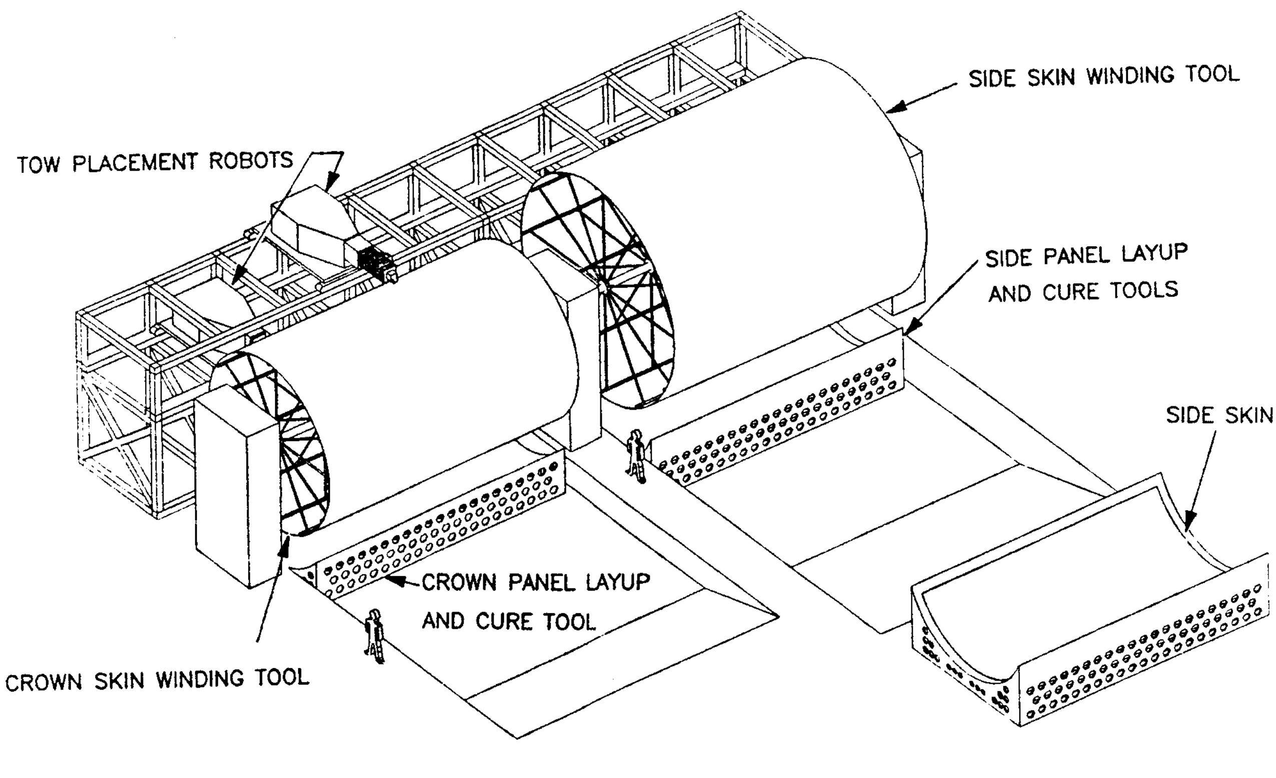



**Figure 4-7: Tow Placement Work Station**

The tow placement work cell also labels and cuts the quadrant panels. The skins are then located onto a female cure mold with vacuum assistance and transported by the

AGV. Locators are either attached or cut into the skin for subsequent locating of curing, trimming, inspection and final assembly details.

### 4.3.2 RTM/Textile Center

The RTM work station (see Figure 4-8) is an integral detail fabrication station for producing the baseline window belt frames, skin splices, and frames for all of the quadrant panels. Repeatable dimensional accuracy is critical for cobonding of precured RTM parts with curved skin panels. The tolerance requirements for the crown and side panel frames are approximately ±0.005 in. along the radius. The frames for the keel panel are not as critical since tolerance pay-off can be realized at the mechanical joints. Since the cobonded frames are considered as an integral part of the skin, fiber architecture, resin, and cure cycle must be properly selected to minimize panel warpage and bond joint voids.

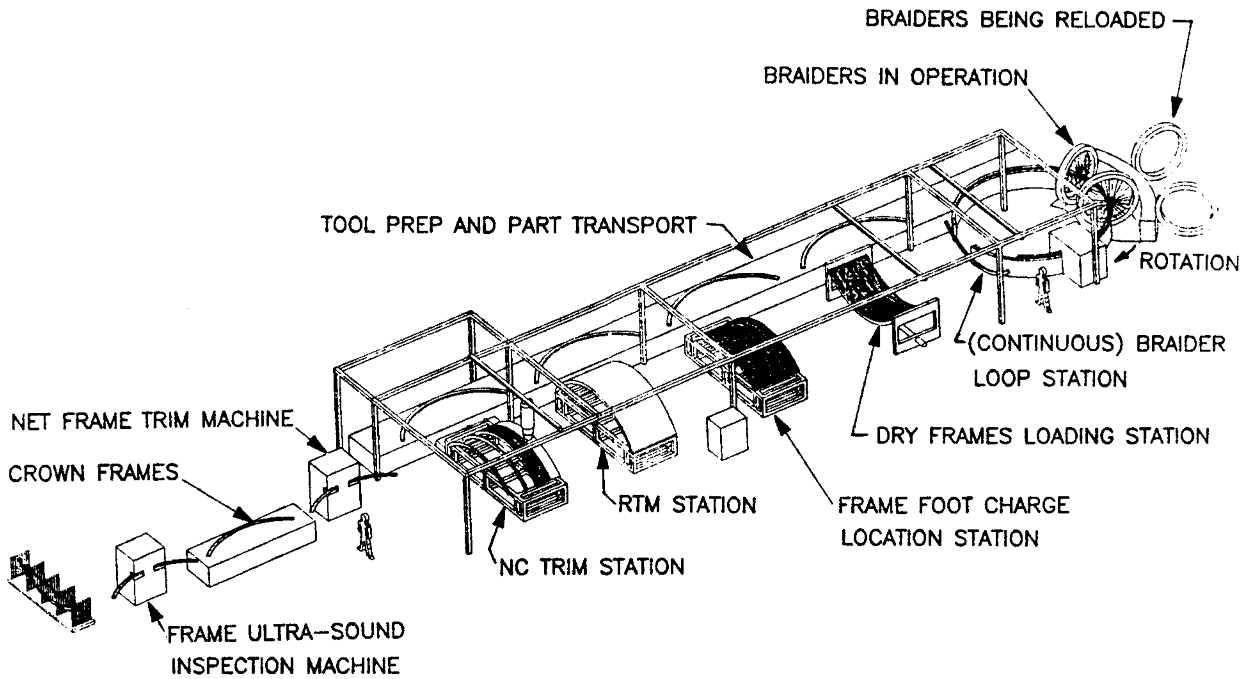



**Figure 4-8: RTM/Textile Work Station**

The textile frame will use advantages of batch mode processing and braiding. When considering RTM processing, resin flow is more dependent on the part length than on the width. Batch processing by placing multiple frames side-by-side appears low risk since the length over which the resin must be drawn is not changed. The frame preform is a triaxial braid. A typical braiding machine (144 carriers) with a automated gantry system can braid up to 4 ft./min. of linear double ply preform. The preform could be fabricated in approximately 20 minutes for a 3-double ply preform that is 15' in length. Current braider configurations have significant down time due to spool size limitations. Large spool sizes from 3-5 lbs. can be achieved by increasing the braider diameter. This can reduce reloading time by 90%.

Three full time braiders would be required for producing five shipsets a month. A transfer system similar to a conveyer belt is used to transfer the mandrels to the braider gantry system. The mandrels are then braided through three braiders in series. It should be noted that a more effective rate may be realized by using individual braiders for each mandrel, pending downtime rates. A transfer system loads the bottom flange fabric and braided mandrels into the mold cavity. After the RTM process, the elements are separated and trimmed in a dedicated parts trimmer.

The keel frames, window belt and quadrant splice members use prestacked fabric with batch mode processing similar to the frame fabrication. The flat splice straps are cut from a large RTMed panel. The keel frame will also have a similar system to the crown frames that will use stitching or binder to form the "T" section of the flange. Actual design and tooling configurations will be developed later in the ATCAS program.

### 4.3.3 Automated Tape Layup and Drape Forming Center

The cocured stringers are fabricated at the work station shown in Figure 4-9. A robotic work station is used to lay down the unidirectional material up to 100 ft./min. with 12 in. wide tape to produce a large charge. The same gantry system is used to rough trim and label the simple charges into the drape forming stringer charges. The individual charges are automatically transferred to a multi-mandrel drape forming operation for net shape forming and net trim. The individual charges and associated soft cure mandrel are transferred either to storage or to the detail assembly work station. The soft stringer cure tooling allows the stringers to conform to skin ply tailoring with minimal extraction difficulty. This has been demonstrated on 50 ft. long hat stringers.

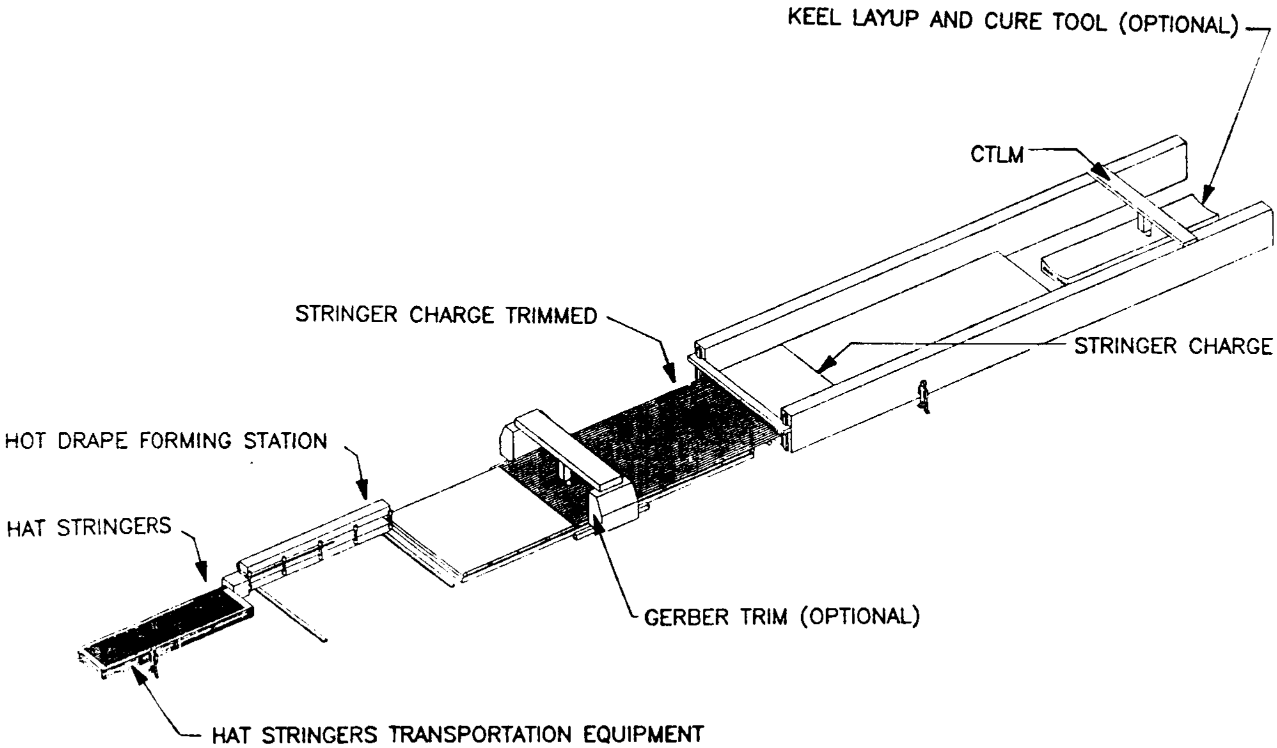



**Figure 4-9: Automated Tape Layup and Drape Forming Work Station**

### 4.3.4 Quadrant Subassembly

This station locates and bags the skin, stringer, and frame panel for cure. The rotisserie tool is designed to locate the individual detail parts for proper placement onto the skin panel. The assembly is done in the reverse mode by first locating the pre-fitted reusable bag onto the rotisserie (see Figure 4-10). The precured inspected frames are then positioned into the bag with supportive cure tooling. Pressure pads are inserted into each mouse-hole to provide stringer cure pressure underneath the frames. After the pressure pads have been inserted, the hat stringer charges and cure mandrels are positioned into the frame grooves. Adhesive is applied to the frame flanges and then the whole subassembly is rotated and loaded onto the uncured skin. Because of the critical nature of skin-frame interface, a frame contour inspection may be required after the application of the adhesive.

In order to transfer the frame and stringer subassemblies to the skin, the rotisserie must be able to hold them in an upside down position. This may be achieved with the use of either vacuum assistance or conductive stringer mandrels in a magnetic field. Once the subassembly is positioned onto the uncured skin, the rotisserie hard points must retract without interfering with the located frames or stringers.

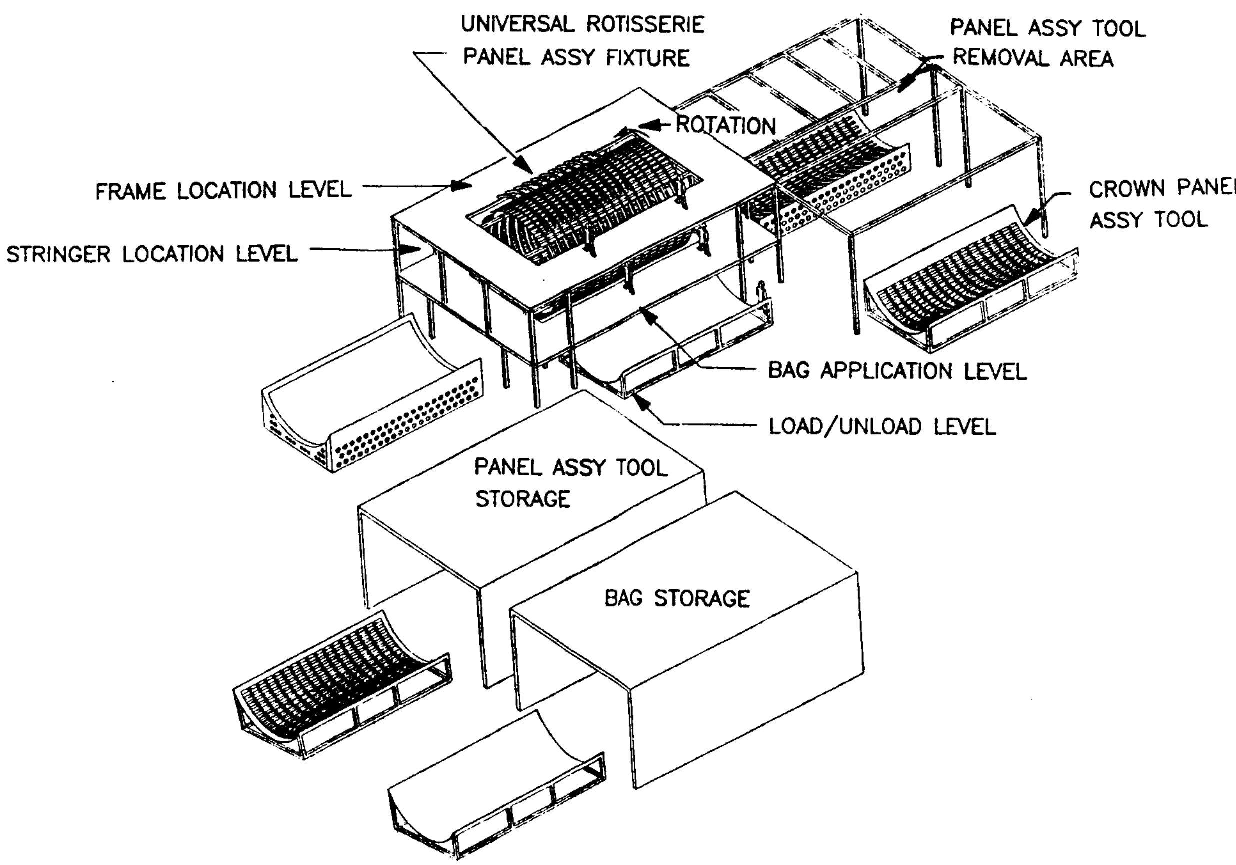



**Figure 4-10: Quadrant Subassembly Work Station**

### 4.3.5 Cure/Cobonding

The quadrant panels are sent to the autoclave (see Figure 4-11) and cured in a batch mode. Only one autoclave (150 in. diameter x 100 ft. length) is required to provide the five shipsets per month. Several batch mode scenarios are possible (Table 4-2), providing scheduling flexibility.

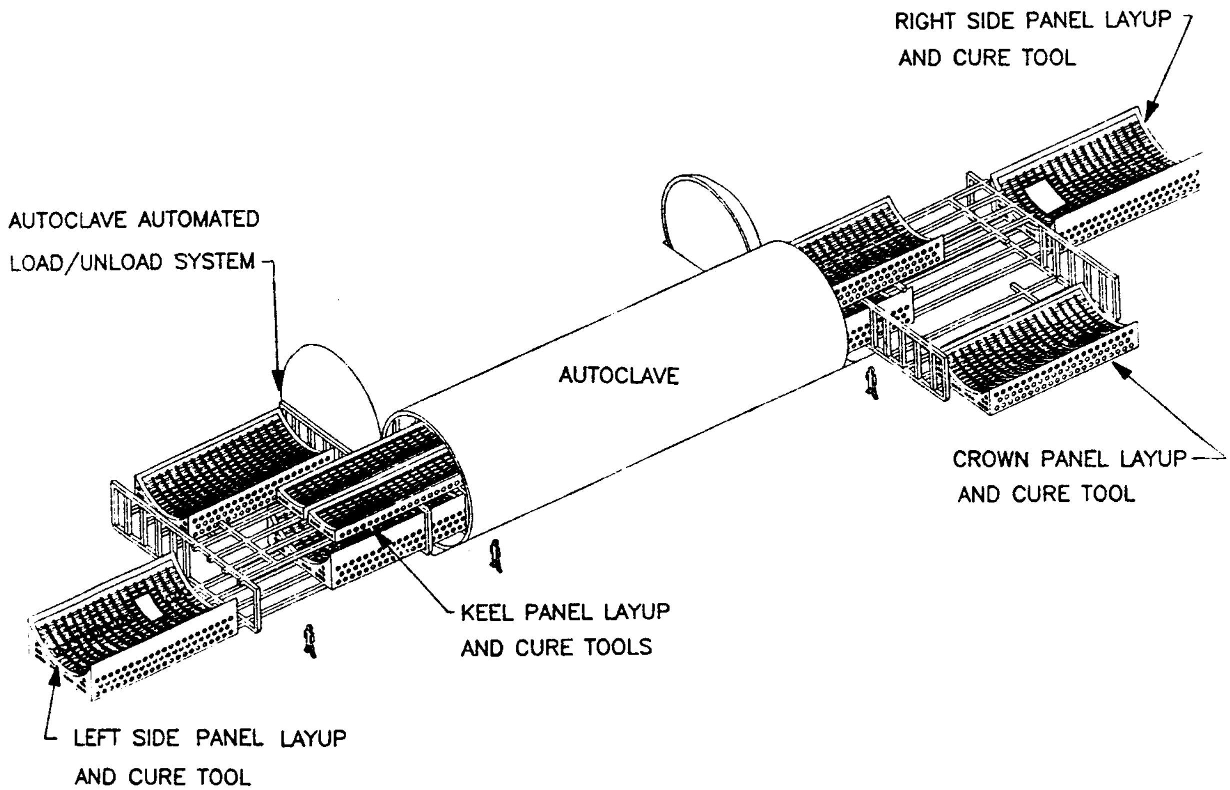



Figure 4-11: Autoclave Work Station

| Options | No. of Panels per Autoclave Run | | |
|---|---|---|---|
| | Crown | Side | Keel |
| 1 | 1 | 2 | 2 |
| 2 | 2 | 2 | |
| 3 | 4 | | |
| 4 | | | 8 |
| 5 | | 2 | 4 |

Table 4-2: Autoclave Loading Options

The autoclave work station will include cure monitoring capabilities to control panel warpage. Warpage control by modified cure cycles may be required for large intricate bonded panels to ensure low void content, resin flow control, minimal temperature gradients within the tools and autoclave.

### 4.3.6 Inspection

The inspection work station that uses nondestructive test equipment is shown in Figure 4-12. All parts are inspected following cure steps. As a result, frames are inspected after RTM processing and the skin-to-frame bond is checked following panel cure. A large immersion tank is used for pulse echo inspection of the skin, frames, stringers, and element-skin bond lines. The immersion tank will use multiple heads that are specific-task oriented. Inspection techniques for braided structure cobonded to laminate skins will be required.

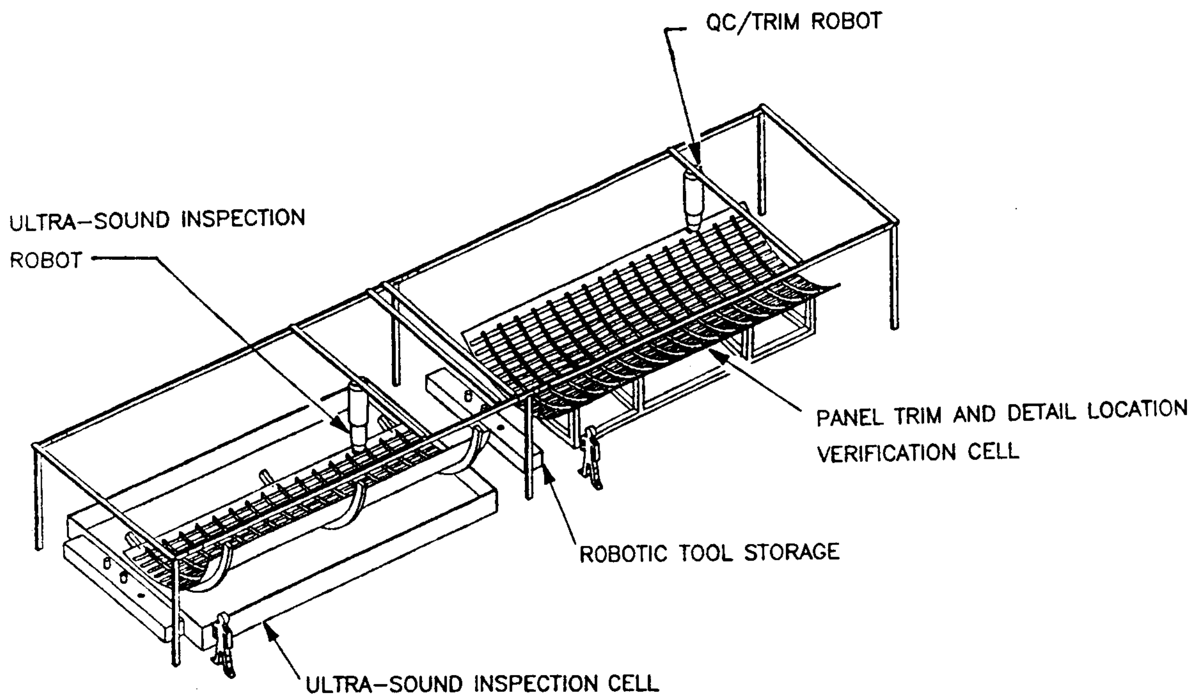



**Figure 4-12: Inspection Work Station**

### 4.3.7 Final Assembly

The final quadrant assembly station (see Figure 4-13) uses an automated fastener installation machine and a gantry system to locate quadrant panels with respect to one another. Once the quadrant panels are aligned, a double multi-task head (inner and outer skin heads) drills the hole, inserts and tightens the fastener through the two overlapping skins and stringer flange. It requires approximately 15 seconds to install a fastener. Time cycle may be decreased by multiple heads working simultaneously. The heads use the attached blade stringer for positioning along the length of the longitudinal splice member. One design feature that allows easy access for fastener installation is the termination of frames prior to the panel edge.

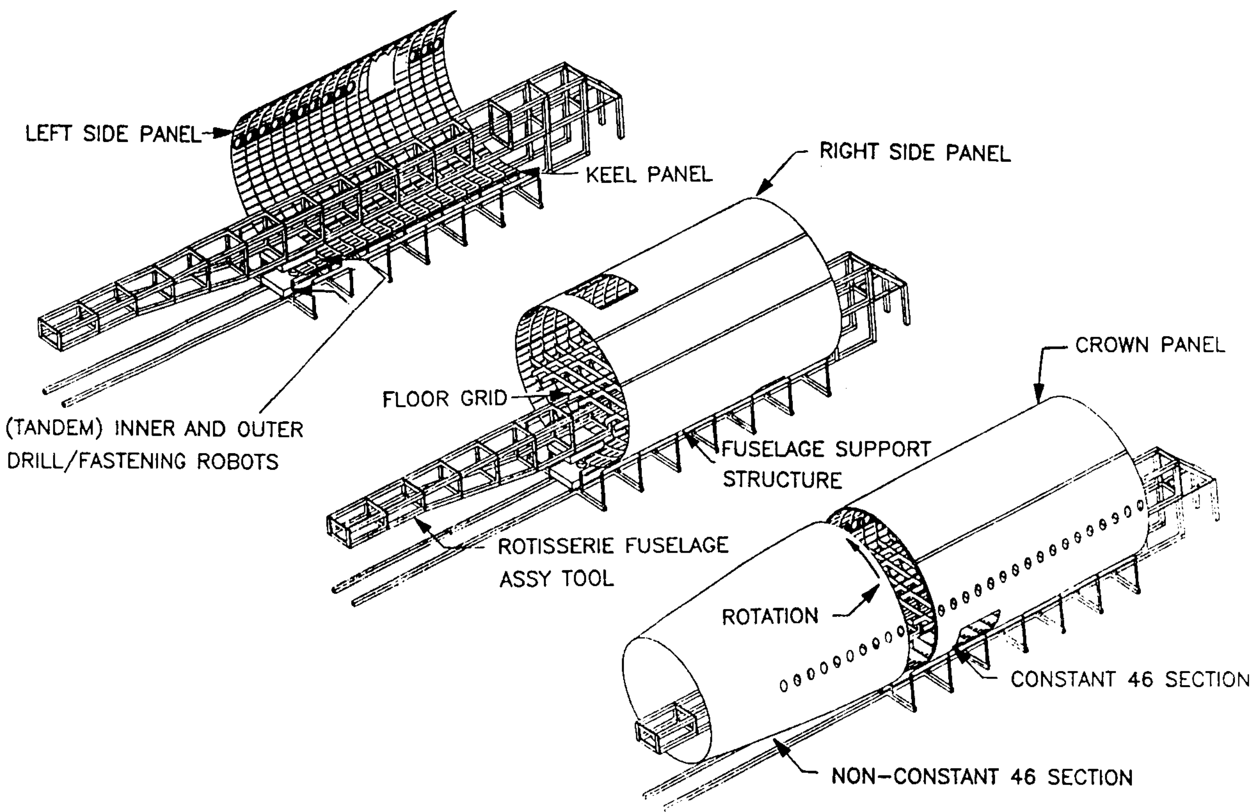



**Figure 4-13: Final Assembly Station**

After the panels have been fastened along the longitudinal splice, the frame splices are installed. The splice plates are selected based on tolerance data obtained at the inspection station.

The circumferential assembly of adjoining sections requires that nearly seventy hat stringers around the circumference be aligned for proper fit-up. To minimize misalignment, hard curing tools can be used to control hat stringer end tolerance during cure. This adds some complexity to the bagging and cure process but reduces downstream major-assembly costs. Another alternative to handle stringer misalignment is the use of innovative stringer splices that have the flexibility to permit misalignment without sacrificing load transfer efficiency. These designs will be evaluated.

The assembly of the circumferential splices requires that the assembly jig locate the two sections while the inner splice plate is positioned. Similar to the longitudinal splice assembly, the robotic head drills through the splice plate and quadrant panels, then installs the fasteners. The stringers splices are then located and checked for shimming on the top and flange areas of the hat. Inspection is required for the blind splice fasteners.

## 4.4 Technical Issues for Baseline Concepts

The most critical manufacturing issue associated with baseline concepts selected for ATCAS relates to final assembly. Crown and side panels have bonded stringers and frames, while the keel panel is sandwich with bonded frames. Although each of these design concepts eliminates element assembly steps and part count, they yield relatively stiff panels. This may lead to potential problems with panel installation and section joining. Figure 4-14 illustrates some of these issues on a diagram of the full crown panel. Variations in locational tolerances of stringers and frames is critical to their alignment at circumferential and longitudinal splices, respectively. Overall panel warpage may also be an issue due to local unsymmetries at bonded elements. High bending stiffness of the baseline panels will limit attempts to deform them into shape prior to splicing.

The ATCAS program plans to address the manufacturing issues shown in Figure 4-14 in several ways. First, analysis will be used to help predict panel distortions and select robust design constraints (e.g., layups and element geometries which minimize the problem). Element locational tolerances and panel warpage will be measured for parts manufactured in ATCAS to judge the magnitude of the problem and confirm predictions. Second, a considerable number of tests are scheduled to address the mechanical performance of splice details. The effects of panel warpage and misaligned stiffening elements and frames will be considered in these testing efforts. Innovative splice concepts that minimize the effects of misalignments will also be designed and tested.

Another critical manufacturing issue is the control of fabrication processes to yield quadrant panels of acceptable quality. Quadrant panel cost benefits assume that large panels will not be rejected due to manufacturing defects. The ATCAS program will address this issue by selecting robust designs and processes which minimize potential problems due to fabrication anomalies. Analysis tools to accurately relate process defects to resulting structural performance will be sought. Simple rework procedures will also be considered to help avoid unnecessary scrapping of expensive parts.

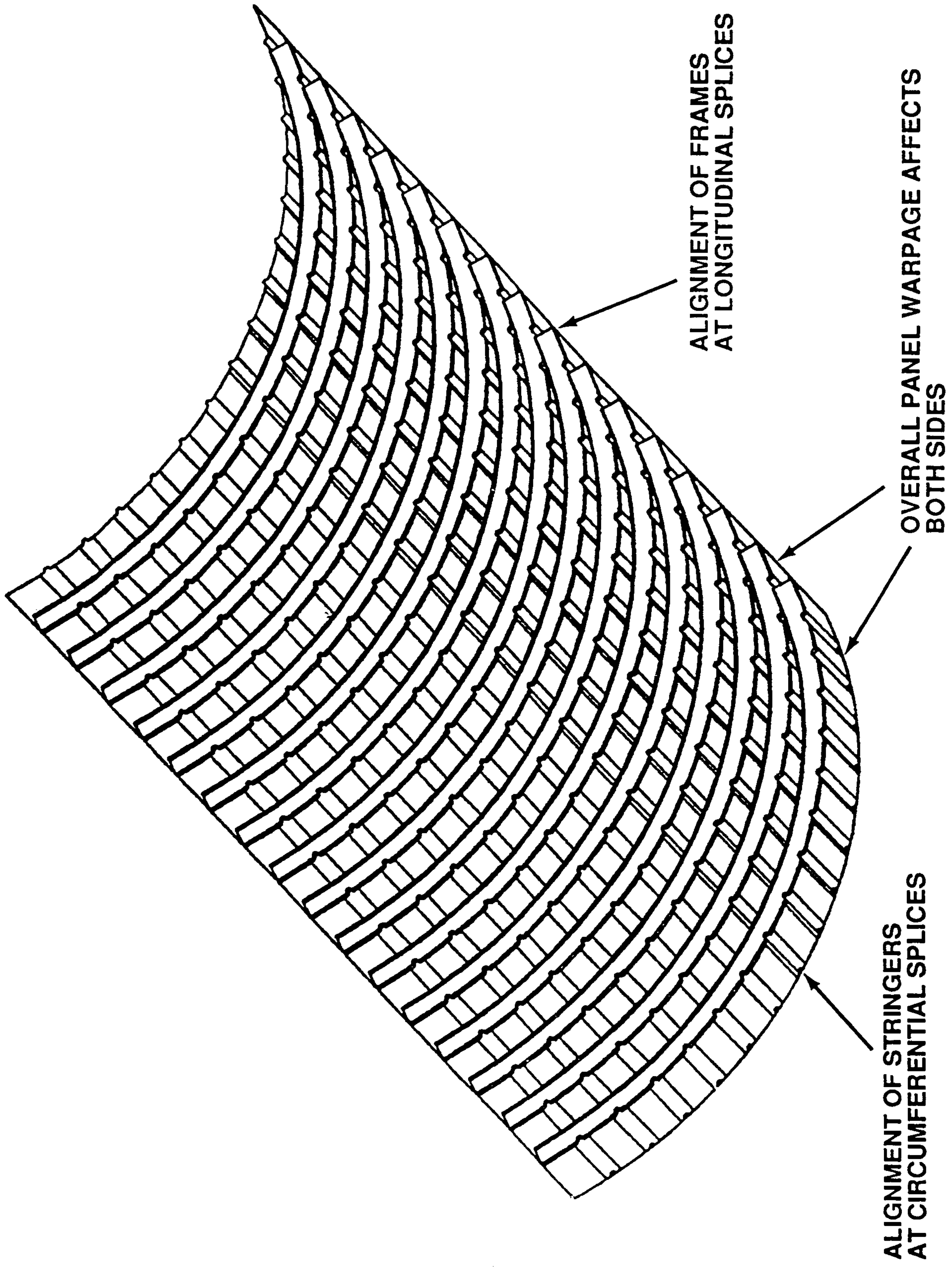



**Figure 4-14: Assembly Issues for the Crown Quadrant Panel**

### 4.4.1 Crown

The fuselage crown area is the simplest quadrant in terms of design detail and manufacturing complexity. A smaller number of technical issues are also associated with the crown. Two critical manufacturing issues were discussed at the beginning of Section 4.4. Other major issues for the crown baseline which will be addressed in ATCAS include:

1. *Hoop tension damage tolerance of panels with large penetrations.* This issue encompasses failsafe pressure loads. The most critical damage geometries for hoop loading are expected to be slender notches oriented along the longitudinal axis (e.g., Ref. 4-1). The effectivity of bonded frames as "tear straps" needs to be determined. The scenario of a penetration that severs a frame and skin must also be studied.

2. *Axial tension damage tolerance of panels with large penetrations.* This issue encompasses failsafe fuselage bending loads. The critical damage geometries for axial loads are expected to be slender notches oriented along the circumferential axis and severing a stringer. Both hoop and axial tension damage tolerance in the crown are expected to yield lower strengths for unidirectional loading cases. For example, biaxial tension in composites tends to yield higher failure loads due to a Poisson effect that reduces ply stresses (see Ref. 4-2). However, the complex stress distribution near a hard point could be most severe (i.e., notches that sever a stringer close to the hard point intersection of a frame).

3. *Axial compression stability of panels with and without damage.* The reversed fuselage-bending load condition for crown panels yields maximum axial compression loads that are approximately 40% of the tension case. Euler panel stability is an issue for this load case due to minimum gage skins which are allowed to buckle. The post-buckled performance of the panel must be demonstrated with and without damage. A worst case condition may involve impact damage in the stiffening element.

4. *Minimum skin gage required to satisfy hail impact criteria.* Structural tailoring in the crown is limited by the minimum skin thickness requirement used to suppress visible damage due to severe hail storm conditions (i.e., 500 in.-lb. impact by 2.5 in. diameter ice balls, usually simulated with lead impactors). This relates to the desire to avoid high repair costs for multiple-site impact damage caused by rare hail storms.

5. *Fiber/resin distribution of frames after RTM processing.* The performance, warpage, and dimensional tolerance control of complex geometries such as curved frames is expected to relate to fiber/resin distribution. Assuming a suitable cure cycle has been established, the fiber/resin distribution of traditional tape and tow materials is most strongly dependent on the prepregging operation. Receiving inspection tests add costs to these materials to ensure prepreg of acceptable quality. Both resin infusion and part cure occur during RTM processing. As a

result, the quality of fiber/resin distribution for a RTM part depends on RTM process control and not the raw material costs. Cost efficient methods of controlling the quality of RTM parts must be established.

6. *Performance of the frame mouse-hole design detail.* This design detail simplifies the skin/frame cobonding operation but adds a stress concentration that needs to be analyzed and tested. The higher stresses near the mousehole may lead to a need for additional frame material. Sufficient damage tolerance for skin penetrations located near the frame mousehole design detail must also be established. The cost trade between reduced bonding labor and increased material requirements needs to be understood to minimize total costs.

7. *Durability of design details (cobonded frames and mechanically fastened splices).* The durability of composite fuselage design details has received little attention in the past. Cyclic pressure load conditions are expected to drive the design of frame-to-skin adhesive joints in the crown. This pressure pillowing problem will need to address creep/fatigue interactions using analysis and tests. Potential bond-surface contamination, resulting from poor handling, can also affect the durability of the frame-to-skin bond. Combined cyclic load conditions also pose a significant problem for longitudinal and circumferential mechanically fastened joints. The combined loads include axial tension/pressure and reversed axial compression/pressure. The effects of environment and real time on damage accumulating in material surrounding the bolt hole will need to be considered.

### 4.4.2 Window Belt (Side)

The fuselage side quadrants have considerably more design detail and manufacturing complexity than the crown. Many of the crown technical issues are also critical to side panel locations above the window belt. The two critical manufacturing issues that were discussed at the start of Section 4.4 (i.e., Panel Warpage/Fitup, Low Rejection Rate) are of greatest concern for the side quadrants due their size. The lower portion of side quadrants (i.e., approaching the keel) have considerable combined load interactions. The combined effects of axial compression, inplane shear, and hoop tension on damage tolerance needs to be understood. Other major issues for the side baseline concepts which will be addressed in ATCAS include:

1. *Several technical issues listed for the crown are also associated with the side quadrant.* These include (1) Hoop Damage Tolerance, (4) Minimum Skin Gage, (5) RTM Fiber/Resin Distribution, (6) Mousehole Design Details, and (7) Durability of Design Details. Note that the side panel load conditions which need to be considered for frame and circumferential splice details are significantly different than for the crown.

2. *Impact damage resistance and tolerance of stiffened panels near the keel.* Numerous in-service impact scenarios are possible in the lower portion of the side quadrant. These include stones, runway debris and ground handling equipment. Studies are needed to ensure that the structure is resistant to damage occurring

for the full range of impact threats and to characterize damage for residual strength predictions. Residual strength models and verification tests must consider the effects of combined compression and shear loads representative of the lower side quadrant. An understanding of material, design, and laminate variables affecting impact damage resistance and tolerance is needed to promote low-cost, robust designs.

3. *Shear stability and damage tolerance near panel cutouts such as windows and doors.* Window and door support structure such as frames, door stops, and intercostals must ensure adequate strength and dimensional stability in areas of shear, axial and pressure load redistribution. Design and fabrication of these elements must consider potential damage scenarios which complicate the load paths. For example, the window frame module is currently planned to be cobonded with the skin; however, potential debonding problems may require through-thickness reinforcement such as composite rivets for adequate performance.

4. *Efficient laminate thickness tailoring at door and window cutouts.* An increase in laminate thickness near large cutouts such as windows and doors is required for stiffness, stability and strength. Since material tends to be a major cost center, it is desirable to understand the manufacturing options and mechanics issues that will enable thickness tailoring to save cost and weight. Efficient processes such as automated tow placement that can drop plies with minimum material waste are sought. Interlaminar stresses that develop near ply drop-offs must be considered in solving the shear lag problem to design ply drop sequences.

5. *Fiber/resin distribution of window frame inserts after RTM processing.* The question of how large of a window belt insert is feasible for RTM processes needs to be answered. Additive dimensional tolerances and warpage must be considered in seeking an answer to this scale-up issue. One 31 ft. long window belt insert would appear to reduce assembly costs, assuming fabrication tolerances can be controlled. Realistically, an upper limit on the desirable size for window belt inserts may be sought. For example, assembly jig and shimming requirements for large parts may add more costs than saved from cutting assembly costs of many small pieces. As with circumferential frames, the desire to attain suitable bond strengths in co-bonded window frame to skin adhesive joints will drive strict cured RTM part tolerances.

6. *Handling and storage of frame, window frame, and door frame design details before and after the RTM fabrication process.* Handling of dry preforms must be considered to avoid distorting the textile weave pattern (e.g., fiber orientation) prior to cure. This includes the operation used to drape preforms into tools for RTM processing. If RTMed parts are fully cured, they must be stored to avoid surface contamination prior to cobonding with side quadrant panels. Alternatively, C-staged parts require special handling that avoids both surface contamination and distortion prior to accurate placement on a tool for cocure with the side panels.

7. *Nondestructive evaluation of complex window and door frame detail geometries.* Nondestructive methods for evaluating the quality of complicated part geometries (e.g., corner radii in window frame modules) need to be developed and demonstrated. Collaborative efforts with structural analysts are also required to determine the effects of defects and hence, support the development of robust designs and quality control specifications. The approach taken in this effort should ask the question: "what manufacturing quality is needed to ensure performance standards?". This approach would avoid specifications that eliminate benign defects and add unnecessary costs to the fabrication process.

8. *Compatibility of stiffening element geometry with door and window design details.* Cost constraints for design optimization tools must consider the added complexity of door and window details when running stringer geometry trade studies for the side quadrant. Detail assembly costs can be minimized by selecting a stiffener geometry that facilitates attachments in door and window regions of the side quadrant. A J-stringer geometry may be the best shape for attachment Compatibility with door and window framing structure, but the trade between fabrication and assembly costs needs to be studied.

### 4.4.3 Keel

The fuselage keel quadrant poses one of the most difficult design challenges for applications of composites to transport fuselage (i.e., load redistribution of high compression loads entering the panel at the keel beam attachment). It also has considerable design detail and manufacturing complexity related to the cargo bay floor. The two critical manufacturing issues that were discussed at the start of Section 4.4 (i.e., Panel Warpage/Fitup, Low Rejection Rate) are of particular concern for the baseline keel quadrant due to its high stiffness. Other major issues for the keel baseline concept which will be addressed in ATCAS include:

1. *Some technical issues listed for the crown and side quadrants are also critical to the keel.* These include crown issues number 5 and 7 (i.e., RTM Fiber/Resin Distribution, Durability of Design Details) for circumferential frames. Note that the loads affecting durability of keel frame-to-panel adhesive bonds are significantly different than those in the crown. For example, the baseline keel frames are approximately 2 ft. deep in order to serve the added purpose of cargo floor support. This geometry adds manufacturing complexity to the textile preform and RTM fabrication processes. Similar concerns must be addressed for the baseline intercostals. Several other technical issues described for the crown and side quadrant also pertain to the keel (e.g., impact damage resistance and tolerance). However, since side and keel baseline designs were derived from different families, a separate description of keel issues will be given below.

2. *Impact damage resistance and tolerance of various keel panel locations.* The thick laminate/sandwich construction for baseline keel panels yield unique characteristics to consider in impact damage resistance and tolerance problems.

Added laminate thickness has been shown to yield higher residual strengths for a given impact energy (Ref. 4-3). However, an understanding of relationships between impact variables, surface damage visibility, internal damage, and residual strength is generally needed for commercial aircraft designs. Curvature may also become an issue for impact damage resistance due to the relatively small shell diameter-to-thickness ratio of a panelized keel concept (Ref. 4-4). Panel curvature effectively adds bending stiffness to the structure during a low velocity impact event. The increased shear stresses for thick, curved, laminates subjected to impact are expected to result in a change in failure mechanisms that needs to be studied before attempting to predict residual strength.

A wide range of combined load conditions exist at different locations within the keel quadrant. The effects of combined compression/shear/pressure load conditions on post-impact residual strength need to be studied. The interlaminar stress load redistribution occurring due to ply drop-offs along the length and width of the keel quadrant will complicate this problem.

3. *Through-penetration damage tolerance of various keel panel locations.* Failsafe design constraints such as through-penetration damage may drive the design of various locations along the keel panel length. For example, added impact damage resistance at the thick laminate end of the panel may be such that ultimate-load/barely-visible-damage criteria cause little strength reduction (note: this can occur when using a maximum impact energy as a threshold). In this case, other damage tolerance constraints or panel stability will drive the design.

   As discussed in keel issue #2, through-penetration damage tolerance will have to consider the effects of combined compression/shear/pressure load conditions. The interlaminar stress load redistribution occurring due to ply drop-offs along the length and width of the keel quadrant will again complicate this problem.

4. *Panel stability with major compression load redistribution.* There is likely coupling between residual strength, stiffness, and stability for a heavily loaded panel such as the baseline keel concept. The design and structural location provide many unique features which have received little attention in the past; analysis and tests are therefore needed to ascertain the key variables affecting stability. As with residual strength, keel panel stability will depend on load redistribution. Local eccentricities of a sandwich panel with internal ply drops and wedged core could be amplified by the presence of damage. The damage resistance of frame and intercostal-to-panel bonds is expected to affect overall stability. The attachment of full-depth frames are crucial to stability along the panel length. Thick laminate stability at the forward end is also dependent on the effectiveness of intercostals for providing a side boundary condition.

5. *Process cure cycle for a panel that is thick laminate on one end and sandwich on the other.* A suitable cure cycle needs to be developed and demonstrated for the baseline keel concept. Traditional low density, composite honeycomb cores are unable to withstand the high pressures needed to cure some toughened matrix

materials. One solution to this problem is to precure laminate portions of the panel prior to adhesive bonding with the honeycomb core. This may prove costly and lead to adhesive bond problems if the precured thick laminate section is warped. Another potential solution is the use of foam core materials that are able to withstand pressures needed for cocuring with the laminate.

6. *Efficient ply tailoring in the area of major load redistribution.* Interlaminar stresses must be considered in selecting ply drop-off sequences as compression loads decrease from the forward to aft ends of the keel quadrant. As discussed for the side quadrant, it is desirable to understand the manufacturing options and mechanics issues that will enable thickness tailoring to save cost and weight. Efficient processes such as automated tow placement that can drop plies with minimum material waste are sought. Analysis and test support will help to select materials best suited for the load conditions. More will be said on this subject in descriptions of the following technical issue.

7. *Laminate and sandwich material forms suitable for applications with the baseline keel.* Strong trade-offs between performance and cost are anticipated by the DBT when attempting to select the optimum keel material. Material characteristics crucial to the keel baseline panel concept include interlaminar-shear load transfer, impact damage resistance, and through-penetration residual strength. Increased interlaminar shear stresses near numerous ply drop-offs in the keel panel suggests a possible need for additional resin to enhance load transfer. This may be achieved by increasing overall towpreg resin content or locally adding adhesive at ply drops. A compliant, toughened adhesive is expected to work best for increasing both the interlaminar shear load transfer and impact damage resistance. Any increase in these properties needs to be balanced against increased material costs. The through-penetration damage tolerance also needs to be studied because it could conceivably drive the design of toughened materials.

   An impact damage resistant sandwich construction is needed for the keel baseline concept. Past studies (e.g., Refs. 4-2 and 4-5) have indicated an inherent weakness in traditional composite honeycomb and polymeric foam materials whereby impact causes significant damage that leads to the loss of facesheet stability and decreased compressive residual strength. One example of potential improvements in impact damage resistance has been shown with higher density core materials. A foam with re-entrant cell structure has also shown potential for impact damage resistance (Ref. 4-6). Other factors affecting the impact damage resistance of advanced core materials for curved sandwich panels need to be studied with experiments and analysis. These include the interactions between facesheet and core variables.

8. *Thick laminate keel panel splice heavily loaded in compression.* Several technical issues need to be considered for heavily loaded mechanical joint attachments between thick laminates. Small fastener diameter-to-thickness ratios affect

laminate bearing capability, and, due to typically low interlaminar shear moduli, will increase fastener flexure. Large holes required to mechanically attach thick laminates directly affect bypass dominated failures and are expected to change the bearing-bypass interaction. On the other hand, some characteristics of a compression loaded joint suggest the potential for improved structural performance (e.g., depending on material type, filled-hole compression failures can be higher than filled-hole tension). Analysis and tests are needed to supplement existing design curves and databases that have been generated using tension load conditions.

9. *Repair of thick laminate/sandwich panels with bonded design details.* Repair is an issue at both ends of the baseline keel panel. Mechanical attachment of repair plates will be difficult for sandwich panel construction. Major repairs involving the base panel and portions of the full depth frames will also be laborious. Bonded repair methods for surface damage will need to consider difficulties in curing portions of thick laminates and sandwich panels in the field. New repair methods that can be performed more simply and with minimum cost are needed for thick laminate and sandwich panels.

# 5.0 CROWN QUADRANT GLOBAL OPTIMIZATION

Global optimization of the crown quadrant for the ATCAS contract was completed during a period of seven months. This process included the development of two design concepts from each of three design families (Families B, C, and D). The detailed manufacturing and assembly plans which were developed from each of these designs were then used for cost estimating.

This section documents the design development effort and the selection of the baseline crown concept. Included are descriptions of the crown design conditions, each design concept, the controlling strength/stiffness criteria, and results of the cost and weight estimates. The cost of major design variables are compared. The process and rationale for selecting the baseline concept are also discussed. Finally, items representing improvement opportunities during local optimization are described.

It should be noted that some results presented in this section differ from those presented in past ATCAS Monthly Technical Progress Reports. Some mistakes in cost estimating were found and corrected. Additional stress analysis performed after the release of the design drawings also revealed inadequacies in the tension damage tolerance of several designs. The cost and weight analyses were performed for the original designs (see representative drawings contained in Appendices A through F. The cost and weight results presented below incorporate modifications required for adequate tension damage tolerance.

## 5.1 Design Conditions

Several criteria were used in the design of the crown quadrant, including safety-related criteria for ULTIMATE, FAILSAFE, and SAFE-FLIGHT conditions. ULTIMATE loads were required to be carried with non-visible damage, FAILSAFE loads with an arbitrarily oriented through-thickness damage up to 8 in. long, and SAFE-FLIGHT loads with an arbitrarily oriented through-thickness damage up to 12 in. long. An economic criterion required that any structure be capable of withstanding 500 in.-lb. of impact energy from hail with no visible damage. The latter criterion resulted in a minimum external skin gage of 10 plies (0.074 in.).

Table 5-1 contains the loading conditions that were considered with the above criteria. The longitudinal and pressure loadings are described in further detail in the following paragraphs.

Preliminary internal loads developed for the Boeing 767-X were used to design the crown panel concepts. In sizing the structure, the internal longitudinal and circumferential loadings were considered separately. This approach was selected for simplicity, and because uniaxial tension was thought to be more severe than biaxial tension for damage tolerance conditions. A more complete evaluation of the combined loads is envisioned during the local optimization process.

| | |
|---|---|
| ULTIMATE | 2.0 * (Maximum Positive Pressure Differential) |
| ULTIMATE | 1.5 * (LIMIT Longitudinal Loads + Maximum Positive Pressure Differential) |
| FAILSAFE | 0.8 * (LIMIT Longitudinal Loads) + Maximum Positive Pressure Differential + Aerodynamic Pressure |
| FAILSAFE | 1.15 * (Maximum Positive Pressure Differential + Aerodynamic Pressure) |
| SAFE-FLIGHT | 0.50 * (LIMIT Longitudinal Loads) |

**Table 5-1: Crown Loading Conditions**

Tension and compression axial LIMIT loads corresponded to positive 2.5 g and negative 1.0 g maneuvers, respectively. The compression loads were obtained as a ratio of the tension loads. As shown in Figure 5-1, the longitudinal loads for these conditions decreased from fore to aft along the panel length, and from centerline to edge across the panel width.

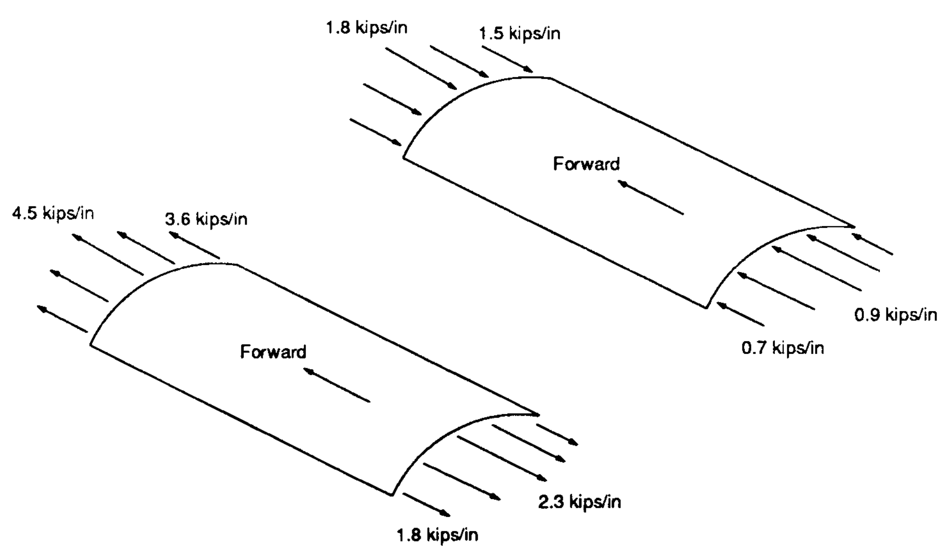



**Figure 5-1: LIMIT Longitudinal Loads for the Crown Quadrant**

The maximum positive pressure differential was 9.0 psi. This corresponded to an ULTIMATE (2.0 * maximum positive pressure differential) hoop loading of 2200 lbs./in., and a FAILSAFE hoop loading of 1257 lbs./in., for a fuselage with a 122 in. radius.

The crown panel designs were constrained by general relationships defining maximum tensile strain levels limiting damage growth, maximum compressive strain levels preventing post-buckling failure, and bolt bearing and bypass strain relationships determining the panel splice strengths. The ULTIMATE (2.0 * maximum positive pressure differential) load case designed the frames and the longitudinal splices. The ULTIMATE longitudinal loads were used to determine column buckling and circumferential joint capability. The minimum margin of safety for this buckling was required to be +0.20. The FAILSAFE condition was more critical than the SAFE-FLIGHT case in defining both the longitudinal and circumferential damage tolerance capability.

Initially, a maximum gross-area tension ultimate strain limit of 0.005 in./in. was employed to account for all damage types in the graphite/epoxy laminate. A more rigorous method for predicting damage tolerance strength (based on References 5-1, 5-2 and Boeing IR&D studies) was developed after the designs and cost analyses were complete. This method indicated that the 0.005 in./in. maximum strain assumption did not provide sufficient tension damage tolerance for the longitudinally oriented FAILSAFE damages in several of the designs. Investigations revealed that slight modifications to the existing designs (i.e. altering ply angles and/or adding 1 or 2 plies) resulted in sufficient capability. Since the required modifications were easily accounted for in the cost and weight estimates, the design drawings were not officially updated.

## 5.2 Design Studies

Two designs were developed from each of three families (B, C, and D). Family B is a traditional skin/stringer/frame geometry, with the stringers cobonded or cocured to the laminate skin. The frames are mechanically attached to the stiffened panel. Family C is also a skin/stringer/frame geometry, with both the stringers and frames cobonded or cocured to the laminate skin. This results in a design with shear-tied frames. Family D is a sandwich geometry, with cobonded frames to provide hoop stiffening.

Each design had a comprehensive fabrication and assembly plan to provide sufficient detail for accurate cost estimations. The following subsections describe each design, and its corresponding manufacturing plans, controlling criteria, and cost/weight results.

### 5.2.1 Design B1

**Design Description.** Representative engineering drawings for Design B1 are contained in Appendix A. The skin and hat-section stringers in this design are fabricated from IM6/3501-6. The skin thickness is constant across the panel width, and tapers slightly along the panel length. The thickness of individual stringers taper along the panel length. Lighter gage stringers are used near the more lightly loaded side panel. The Z-section frames are fabricated from AS4/3501-6 fabric. Stringer clips are used to mechanically fasten the frames to the stringer flanges.

**Manufacturing Plans.** The fabrication/assembly plan for Design B1 uses a variety of manufacturing technologies for the subcomponents. The skins are tow placed using batch processing to minimize material waste. The hat stringers are fabricated by hot-drape-forming flat charges produced with a CTLM, then cocuring them with the skins. The constant height of the stringers allows the use of extractable, reusable soft tooling that conforms to skin tapers. The precured Z-section frames are fabricated by compression molding hand-layed-up prepreg fabric charges.

The assembly of the barrel section is divided into two subassembly processes. For a given frame station, all frames, frame splices and frame posts are assembled into a full barrel hoop frame. After all hoop frames are assembled, they are located onto a rotating fixture that aligns and maintains the proper frame spacing. The precured stiffened skins are then located and secured individually to the frames with the aid of the panel indexing holes. Automatic shimming measurements are completed and the predrilled clip is located and fastened to the frame and skin. When all clips for a quadrant panel are fastened, the next adjacent quadrant panel is located onto the frame hoop, and the skins robotically fastened along the longitudinal lap splice. The crown panel is located first, with the side and keel panels following, respectively. This sequence provides the correct longitudinal overlap requirements.

The completed barrel section is then mated to the adjoining section and fastened together with an internal circumferential splice plate. The one piece hat stringer splices are then shimmed and installed. In order to inspect the blind fasteners, an inspection hole on the side of the hat splice is required.

**Design Drivers.** At the forward end of the centerline stringer, the critical design constraints are a balance between the longitudinal and hoop damage tolerance. Buckling margins become critical near the sides of the crown panel at the forward end due to the lighter stringer gage in those regions.

At the aft end of the panel, the minimum gage criterion is encountered. The hoop damage tolerance criterion is also a controlling factor. The longitudinal buckling margins are small at the stringer ply drop-offs. Large margins are encountered for the axial damage tolerance condition due to the minimum gage requirement.

The longitudinal joints are designed by bearing/bypass strength. The skin laminates are padded with additional plies as required for bearing strength.

The circumferential joints at the ends of the panel require consideration of both a skin laminate splice plate and a stringer splice member. Fastener bearing is the most common driver, requiring localized thickening of both the skin and stringer laminates. The axial loads used to design the joint are augmented by local eccentricity-induced bending loads. The stringer-splice access hole (required for visual inspection of the installed blind fasteners) necessitates additional plies at the center of the stringer splice member to account for the stress concentrations.

Frames and frame splices are designed to carry the maximum bending loads and 15% of the hoop tension load resulting from the ULTIMATE (2.0 * maximum positive pressure differential) load case. The frame inner chord is limited by the 0.005 in./in. maximum allowable tensile strain.

**Cost/Weight Results.** The results of the study show that this design concept is 115% of the cost of 767-X baseline concept and 49% of the weight.

The division of weight between various portions of the structure is illustrated in Figure 5-2. Skins contain the vast majority of weight, with the stringers also being a major weight center.

The relationship between recurring and nonrecurring costs for this design family are shown in Figure 5-3. As can be seen, the recurring costs are dominant, consisting of approximately equal material and labor (assembly + fabrication) components.

In Figure 5-4, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. The recurring element fabrication costs are clearly dominant. The recurring assembly and installation costs are a significantly lower portion than those of the typical aluminum design, shown in Figure 2-1. Lower assembly costs for the composite crown design relates to bonded stringers and the quadrant panel approach which minimizes longitudinal splices. The non-recurring costs are evenly divided between those associated with element fabrication and those associated with bonding and assembly/installation.

The recurring material and labor costs for each major manufacturing step are shown in Figure 5-5. The skin, stringer and frame fabrication costs are the primary cost centers, with panel bonding and frame splice fabrication also being significant. Efficiency of the quadrant tow-placement process is illustrated by the very low proportion of labor to material costs in the skin fabrication.

### 5.2.2 Design B2

**Design Description.** Representative engineering drawings for Design B2 are contained in Appendix B. The skins and blade stringers in this design use AS4/3501-6 material. The skin thickness is constant across the panel width, and tapers uniformly from the forward circumferential joint until minimum gage is achieved. The stringer thickness is constant along the panel length, a requirement necessitated by the desire to include a pultruded stringer design. Lighter gage stringers are used near the more lightly loaded side panel. The Z-section frames use a 2-D braided composite, equivalent to AS4/3501-6.

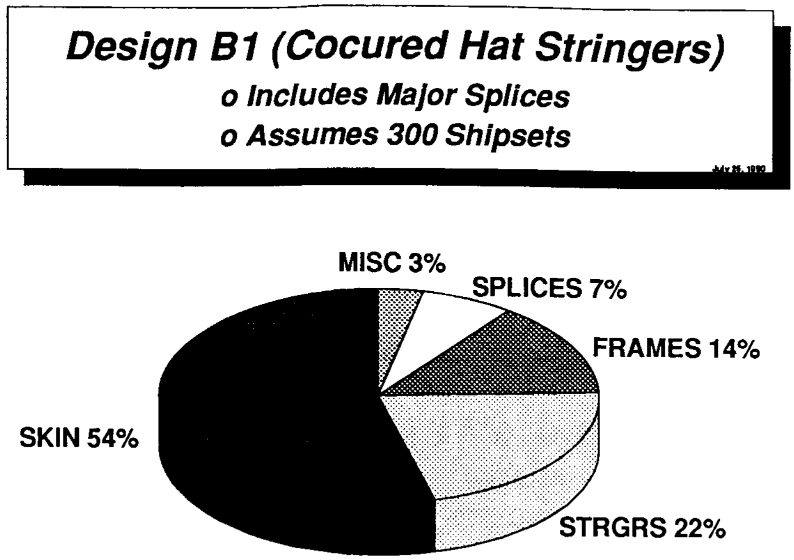



Figure 5-2: Weight Breakdown of Design B1

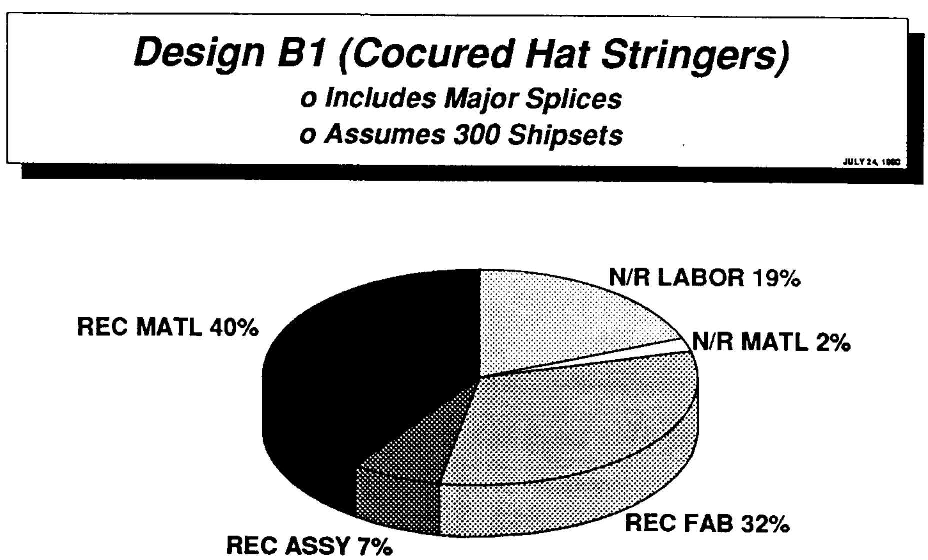



Figure 5-3: Recurring and Non-recurring Costs of Design B1

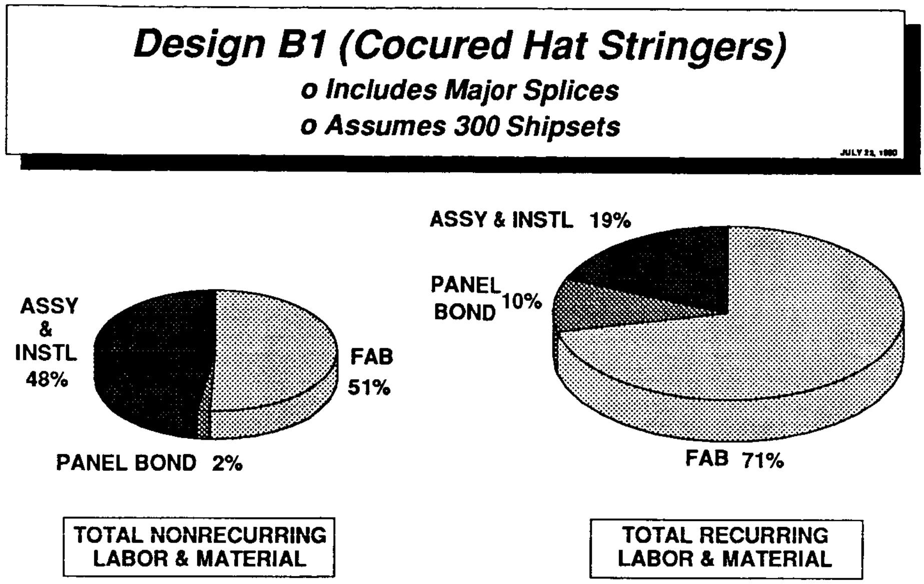



Figure 5-4: Breakdown of Recurring and Non-recurring Costs of Design B1

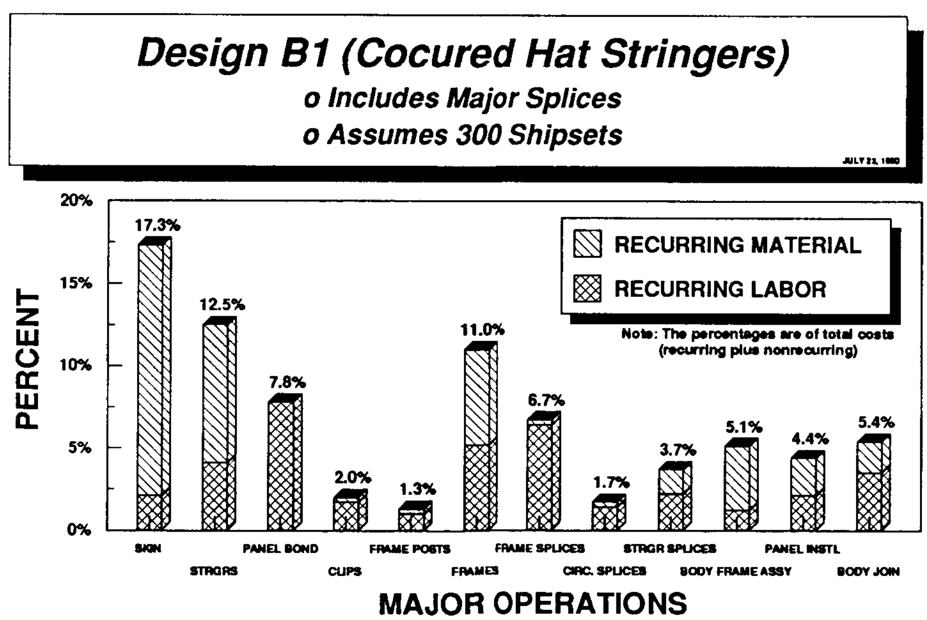



Figure 5-5: Recurring Costs by Major Operation of Design B1

**Manufacturing Plans.** The skins of Design B2 are tow placed using the batch process. The blade stringers are pultruded, using a prekitted prepreg material form, and fully cured. The skin taper is very gradual (approximately 1 ply per foot of panel length), to avoid the stringer post-forming processing required to accommodate skin joggles. Manufacturing demonstrations indicate that thin stringer configurations, can be cobonded to a slightly-tapered skin without reducing bond integrity. The Z-section frames are batch-RTMed braided preforms (4 in a single operation). The 0° fibers provided by triaxial braiding help maintain fiber orientation during the braiding and RTM processes.

The assembly of the barrel section for this design is similar to that of Design B1, except for the elimination of the frame posts. The assembly of adjoining barrel sections is also similar, except that the blade stringer splice is comprised of two pieces.

**Design Drivers.** Design B2 includes a 12 ply (0.088") minimum skin thickness (for axial and hoop damage tolerance requirements), with an 8-ply padup at the forward end and a 1-ply padup at the aft end (for skin bearing requirements). The thicker minimum gage compared to Design B1 (12 versus 10 plies) is a result of the reduced material properties of the AS4/3501-6. The hoop damage tolerance margins are critical throughout the aft section of the crown panel. Axial damage tolerance margins define the locations of the ply drop-offs in the skin. Stringer gage is defined through bearing requirements at the forward end, which is the most heavily loaded. Because of the heavy blade stringers and the skin layup necessary to attain damage tolerance requirements, buckling margins of safety are not critical.

The circumferential skin splice plate and stringer splice members are sized by bolt-bearing, due to a combination of axial load and eccentricity-induced bending loads. Stringers bolt-bearing margins are very large at the aft end due to the constant gage, carried from the forward end.

Longitudinal splices require a single ply added along the panel edge for bolt-bearing requirements.

The frame, although different from Design B1 in material form and manufacturing process, is designed to the same loads and assumptions, with an assumed 15% of the hoop tension load included with the appropriate bending load. The manufacturing method (2-D braided preform/RTM) requires a constant thickness frame cross-section. Inner chord tension and fastener bearing at the frame splice define the remaining-section thickness. Frame splice members are designed to the same loading conditions as the nominal frame section.

**Cost/Weight Results.** The results of the study show that this design concept is 111% of the cost of 767-X baseline concept and 53% of the weight.

The division of weight between various portions of the structure is illustrated in Figure 5-6. As in Design B1, the skin contains the vast majority of weight, with stringers also being a major contributor.

The relationship between recurring and nonrecurring costs for this design are shown in Figure 5-7. As in Design B1, the recurring costs are dominant, consisting of approximately equal material and labor (assembly + fabrication) components.

In Figure 5-8, recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. Very little difference was observed between these results and those of Design B1.

The recurring material and labor costs for each major manufacturing step are shown in Figure 5-9. As in Design B1, the skin, stringer and frame fabrication, and panel bonding are the four largest cost centers. However, the proportion of costs contributed by each are significantly different. Lower skin costs reflect the use of the less-costly AS4 fiber system. Stringer costs are significantly higher, despite the use of AS4 fibers. This is due to a very costly prekitted material form used for the pultrusion process. Reduced frame costs indicate that the braided/RTM process is less costly than the fabric/compression molding process used in Design B1. Increased panel bonding costs reflect the use of adhesive and the more complicated bagging procedure required for the blades.

### 5.2.3 Design C1

**Design Description.** Representative engineering drawings for Design C1 are contained in Appendix C. Only the frame manufacturing and design details differentiate this design from Design B1. The skins and hat-section stringers both use IM6/3501-6 material. The braided J-section frames use a material system equivalent to AS4/3501-6. Frame flanges are cobonded to both the skin and the hat stringers, eliminating the stringer clips, frame posts, and associated mechanical fasteners contained in Design B1.

**Manufacturing Plans.** The skins, edge build-ups, and splice straps of this design are tow placed. The hat stringers are hot-drape-formed in a batch process. The J-section frames are RTMed in a batch process (16 frames at once) using triaxial braided preforms. The closed molds of this process provide the ±0.005 tolerance required for minimal bond thickness.

The cobonded frames of this design reduce the part count and the assembly costs, as compared to Designs B1 and B2. The cure tooling and bagging required for the bonded frame concept has additional complexity when compared to the mechanically attached frame concepts, since the bag must enclose the frame as well as the stringer. The tolerance requirements for the stringer/frame location and the cobonding surfaces are demanding. The use of a sacrificial adhesive layer on these bond surfaces provides some relief to the tolerance demands. A net-shape reusable bagging system is used both to locate the stringers and frames in the quadrant subassembly operation, and to provide compaction pressure. The panel build-up operation prior to curing is as described Section 4.3.4, except without the pressure pads between the frames and stringers.

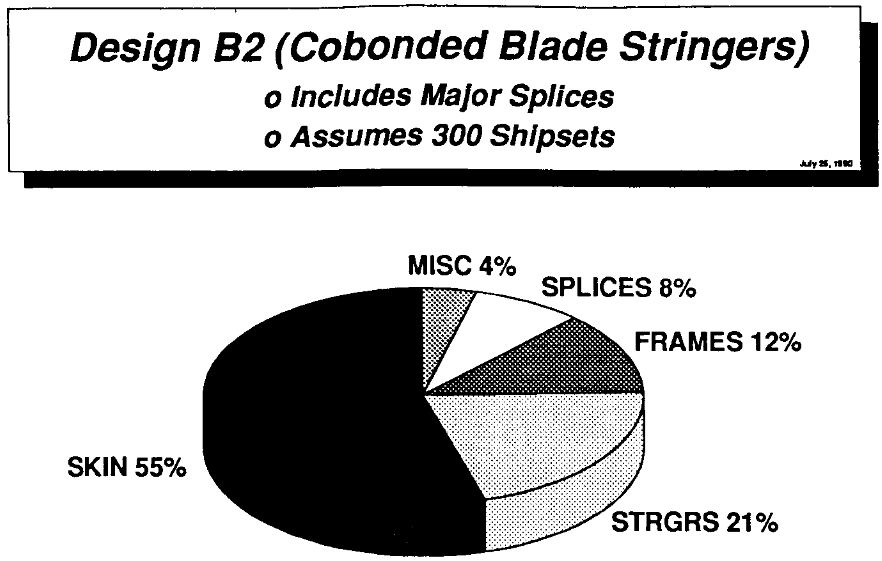



Figure 5-6: Weight Breakdown of Design B2

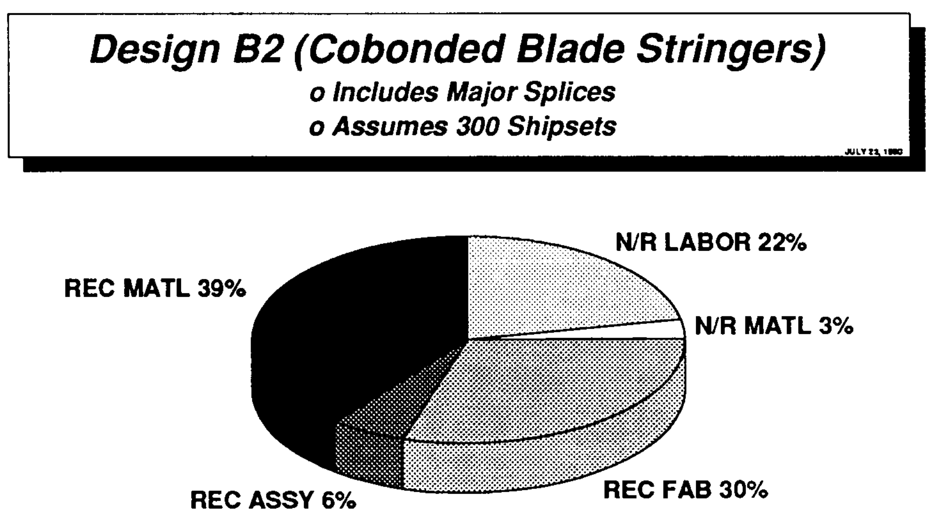



Figure 5-7: Recurring and Non-recurring Costs of Design B2

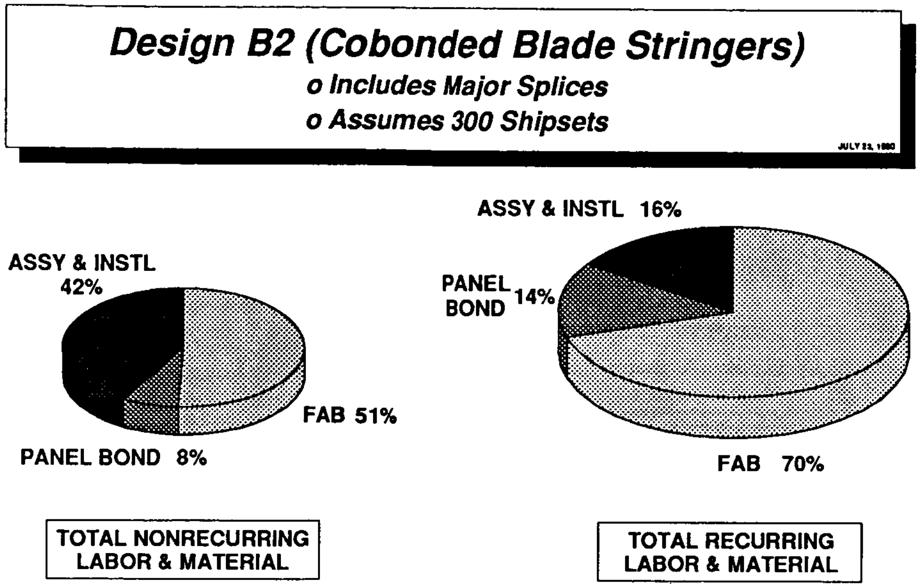



Figure 5-8: Breakdown of Recurring and Non-recurring Costs of Design B2

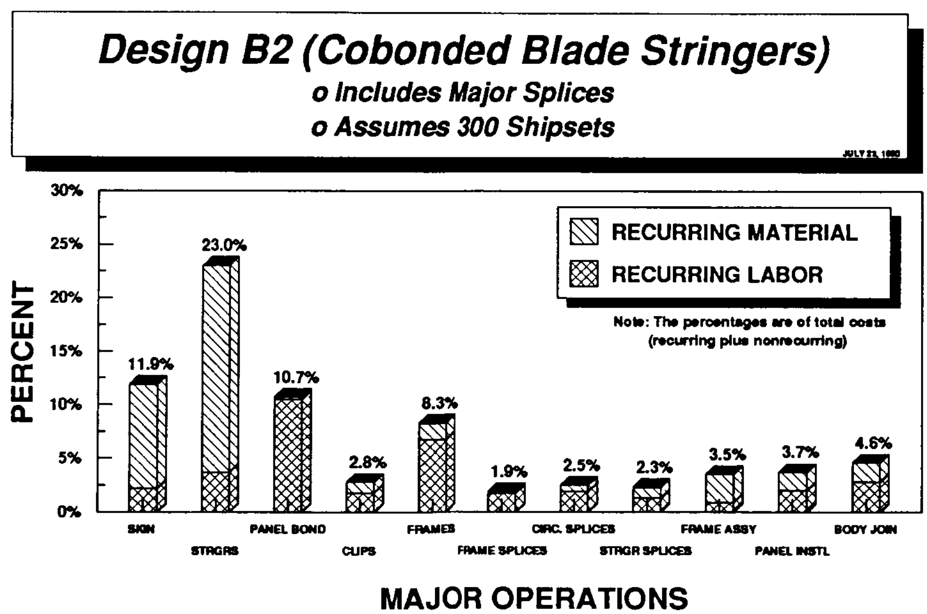



Figure 5-9: Recurring Costs by Major Operation of Design B2

The cocured frames require an approach different than that used for Designs B1 and B2 to assemble the quadrant panels into a barrel section. After the individual quadrant panels have been fabricated and inspected, they are transferred to the final barrel section assembly work station. The multifunctional panel indexing holes are used to position and secure the panels relative to one another within the assembly jig. The automated fastening system then drills, inserts, seals and fastens the bolts along the length of the longitudinal joint stiffener. The frame splices and required shims are selected, located and installed at all frame locations. The individual panels are attached in the order described for Design B1.

After all longitudinal splices and frame splices have been joined, the completed section is then mated with an adjacent section with the circumferential internal splice plate. The same automated fastening system is used for the circumferential splice plate. The last panel splice members are the stringer splices. Misalignment of the stringers is measured robotically to determine shimming requirements. The shims and stringer splices are then located and fastened along the circumferential splice.

**Design Drivers.** The design drivers for this concept are identical to those for Design B1. The frame, which differentiates this design from Design B1, is designed to the same bending loads associated with the ULTIMATE (2.0 * maximum positive pressure differential) load condition, along with an assumed 15% of the hoop tension load normally associated with skin loads.

**Cost/Weight Results.** The results of the study show that this design concept is 107% of the cost of 767-X baseline concept and 50% of the weight.

The division of weight between various portions of the structure is illustrated in Figure 5-10. When compared to Designs B1 and B2, the Design C1 frame weight is a larger portion, and skin weight a smaller portion, of the whole. These changes are attributed to the deeper frame sections.

The relationship between recurring and nonrecurring costs for this design family are shown in Figure 5-11. These relationships differ only slightly from those of Designs B1 and B2, with the recurring costs still dominant.

In Figure 5-12, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. The major differences observed between these relationships and those for Designs B1 and B2 are the increased recurring panel bonding costs and somewhat reduced assembly/installation costs. These are both attributed to the use of cobonded frames.

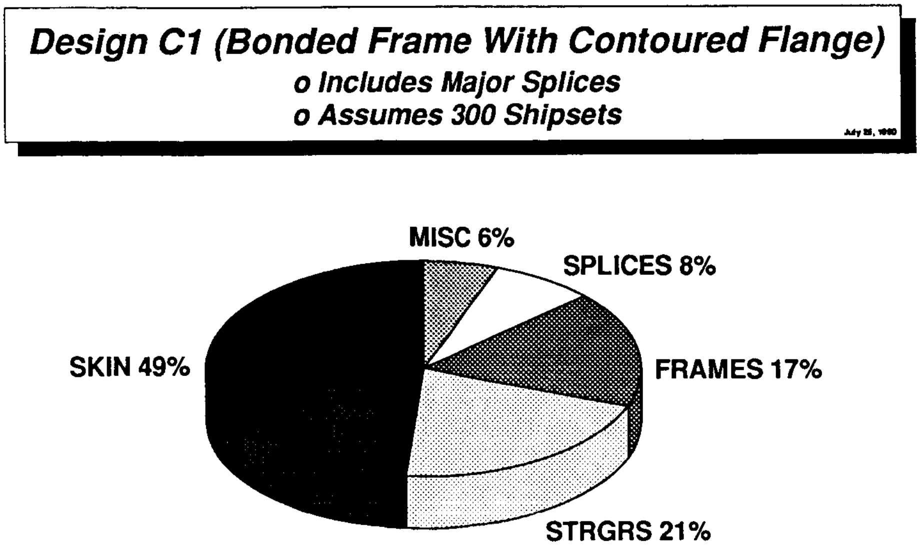



Figure 5-10: Weight Breakdown of Design C1

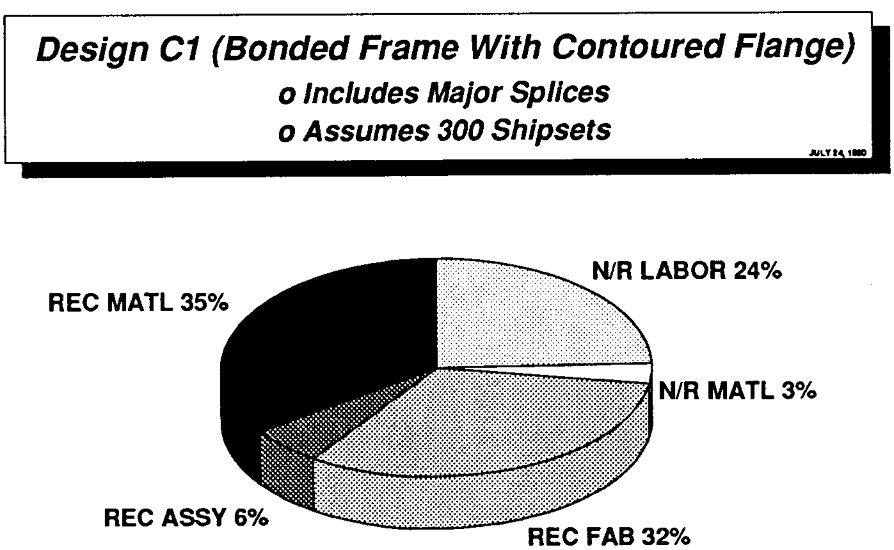



Figure 5-11: Recurring and Non-recurring Costs of Design C1

The recurring material and labor costs for each major manufacturing step are shown in Figure 5-13. As in Designs B1 and B2, the skin, stringer and frame fabrication, and the panel bonding are major cost centers. The proportions of these centers, however, differ from both Family B designs. Skin and stringer fabrication costs are similar to Design B1, owing to the same design of those components. Frame costs are similar to those of Design B2, reflecting the use of the braid/RTM process in both. Significantly higher panel bonding costs in this design are due to a difficult continuous bond of the frames to stringers.

### 5.2.4 Design C2

**Design Description.** Representative engineering drawings for Design C2 are contained in Appendix D. The stringer and frame details differentiate this design from Designs B1 and C1. IM6/3501-6 material is used for both the skins and the hat-section stringers. The Design C2 stringers are constant thickness and height-tapered. This differs from the constant height, thickness-tapered hat concept of Designs B1 and C1. The stringer splices also differ due to these stringer modifications.

The J-section frame is fabricated from a combination of carbon (AS4) continuous and long-discontinuous-fibers (LDF®) in a thermoplastic (PEKK) material system. A novel resin powder impregnation technology which is projected to reduce the material costs of thermoplastic prepregs was assumed. The 45° and 90° plies contain continuous fibers and 0° plies are LDF. The frame is cobonded to the skins and stringer flanges (instead of the skin and entire stringer cross-section, as in Design C1), with "mouse-hole" cutouts at the stringers.

**Manufacturing Plan.** The skins for this design are tow placed using batch processing. The splice straps, however, are cut from knitted prestacked fabric that is RTMed. The height-tapered hat stringers are fabricated by hot-drape-forming flat charges produced with a CTLM. A batch process is again employed for the stringer draping. Custom tooling and cure mandrels will be required for the individual hat stringers. Frames are fabricated by roll forming, followed by stretch forming, and then machining the mouse-hole cutouts.

The mouse-hole frame concept provides some relief from the bonding-surface and locational tolerance requirements of Design C1. Sacrificial adhesive is again used between the bonding surfaces. The cure tooling, bagging, and panel-buildup concepts are similar to those of Design C1, with additional pressure pads required between the frame mouse-holes and the hat stringers to provide curing pressure to the latter. It is assumed that the frame material tolerates an epoxy cure cycle without supportive tooling during cure.

The assembly of the quadrant panels into barrel sections, and the barrel section mating operation for this design are both the same as for Design C1.

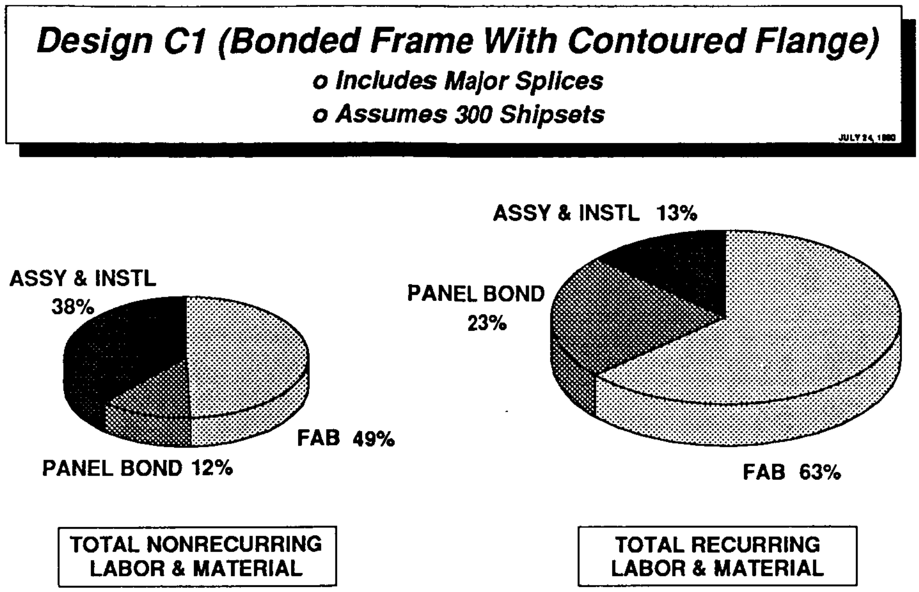



Figure 5-12: Breakdown of Recurring and Non-recurring Costs of Design C1

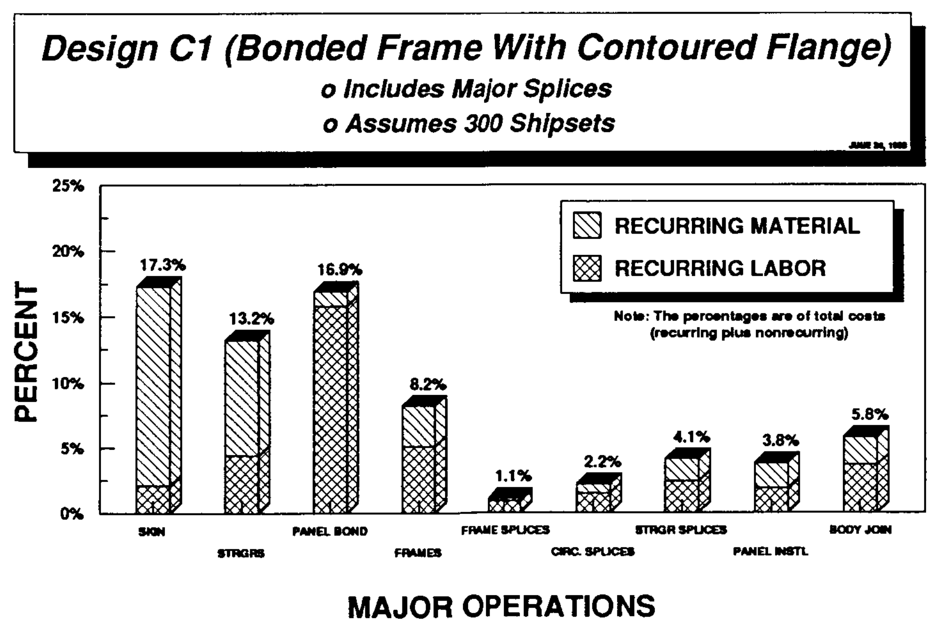



Figure 5-13: Recurring Costs by Major Operation of Design C1

**Design Drivers.** The skin laminate is dominated by the FAILSAFE damage tolerance hoop tension condition. Axial damage tolerance at the forward end of the panel defines the stringer laminate. The stringer height is determined by the minimum allowable buckling margin, which is critical along the entire panel length. Skin ply drop-offs are included towards the middle of the panel length, the specific location determined by buckling and axial damage tolerance capability.

The longitudinal splices are designed to resist the bolt bearing and bypass strain requirements. Skin padups are added as required. The circumferential splices are similar to those developed for Design B1. Geometric modifications are necessary due to a different stringer shape at the forward end, and some additional plies are required in the stringer to carry the fastener bearing load. These additional plies at the forward end complicate fabrication of the stringer laminate. Stringer-laminate padups are not required at the aft end circumferential splice.

Stress concentrations at the mouse-holes result in a much thicker laminate for frames than used in other designs (e.g. Design C1). The most apparent option to this thicker frame is to include an additional flange just over the mouse-hole. While this may reduce the weight, it significantly increases the manufacturing complexity.

**Cost/Weight Results.** Results show that this design concept is 117% of the cost of 767-X baseline concept and 55% of the weight.

The division of weight between various portions of the structure is illustrated in Figure 5-14. The increased relative frame weight is due to the mouse-hole concept.

The relationship between recurring and nonrecurring costs for this design family are shown in Figure 5-15. These relationships differ only slightly from those of Designs B1, B2, and C1, with recurring costs still dominant. The percent of recurring material costs are somewhat higher for C2 because of the use of thermoplastics for frames.

In Figure 5-16, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. The reduced recurring panel-bonding costs relative to Design C1 are attributed to the less-complex bonding requirements of the mouse-holed frame design. These costs are still higher than Designs B1 and B2, again due to the use of cobonded frames. When compared to Designs B1, B2, and C1, approximately 10% of the non-recurring costs shift from fabrication-related to bonding- and assembly/installation-related. This is attributed to low nonrecurring frame fabrication costs.

The recurring material and labor costs for each major manufacturing step are shown in Figure 5-17. The most significant difference between Designs C1 and C2 is the higher frame costs of the latter. This is attributed to relatively high costs of the thermoplastic material form in conjunction with increased frame weight necessitated by the mouse-hole concept. The cost of a thermoplastic frame concept would benefit from a more weight efficient design.

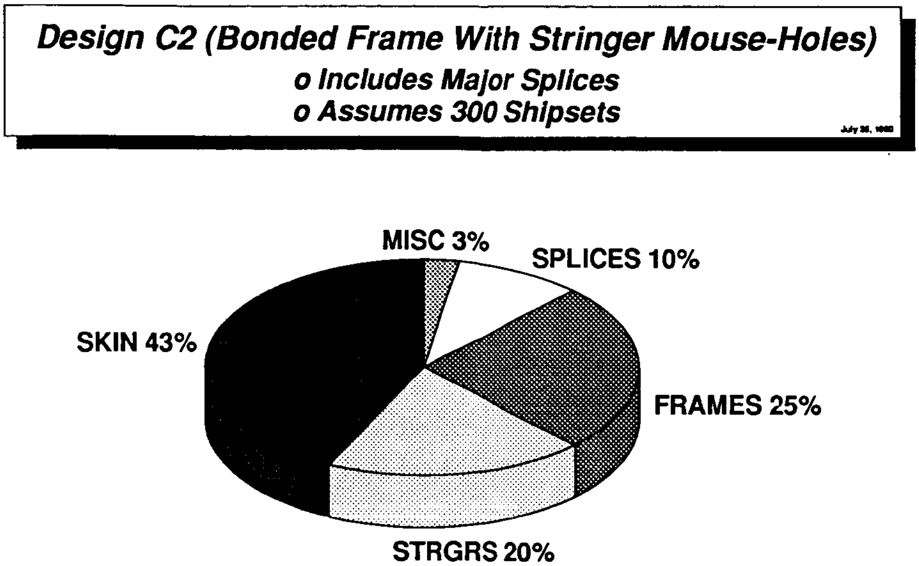



Figure 5-14: Weight Breakdown of Design C2

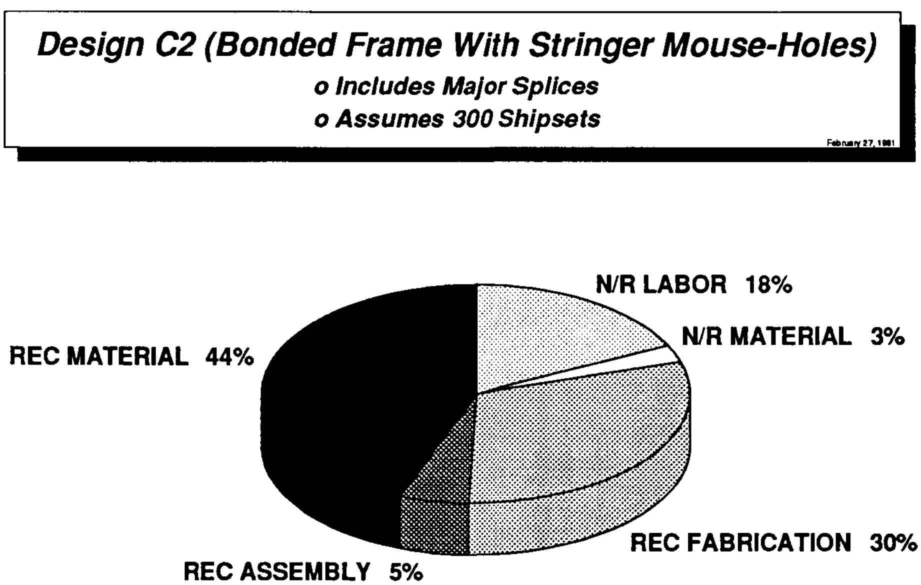



Figure 5-15: Recurring and Non-recurring Costs of Design C2

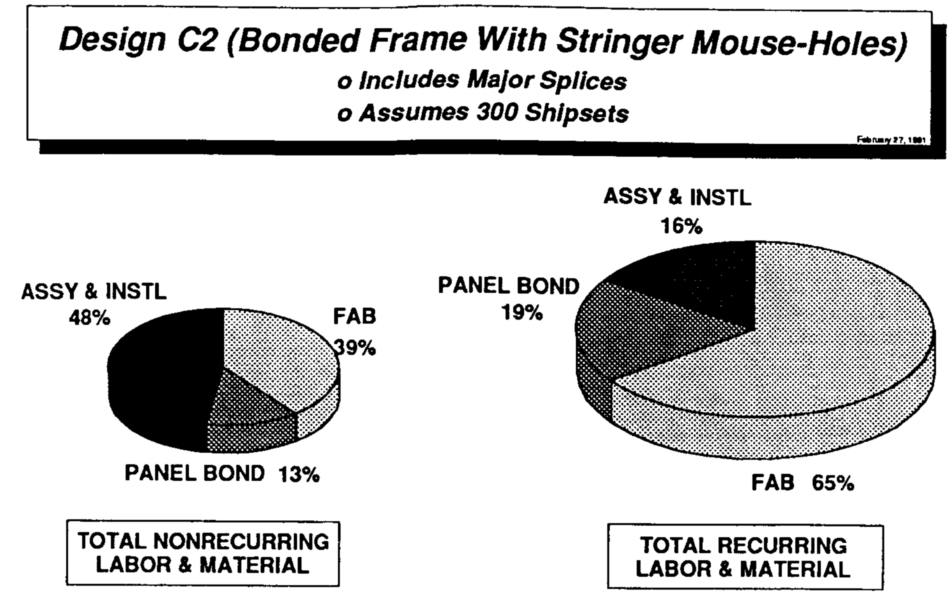



Figure 5-16: Breakdown of Recurring and Non-recurring Costs of Design C2

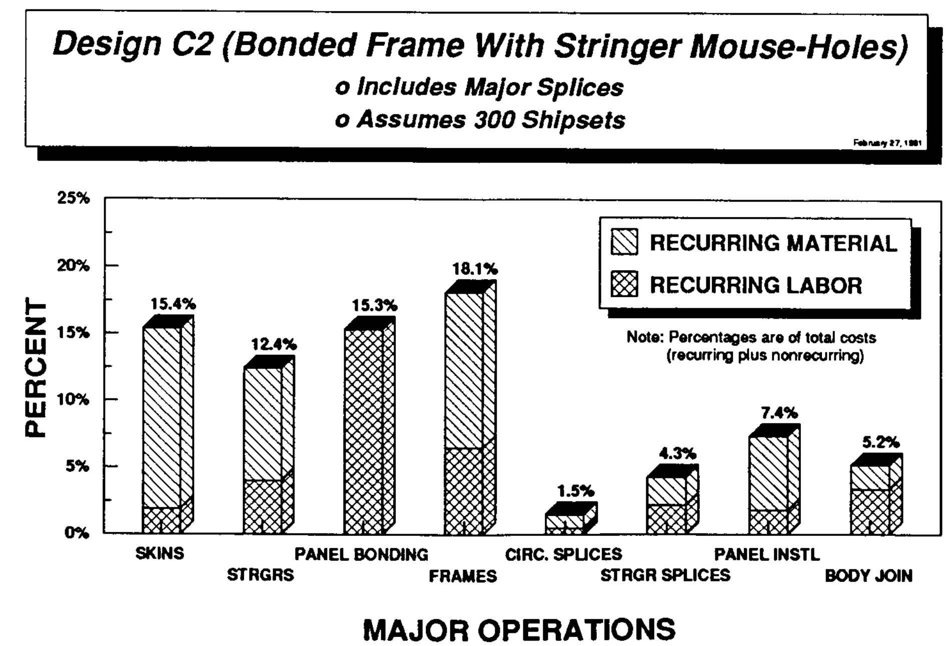



Figure 5-17: Recurring Costs by Major Operation of Design C2

### 5.2.5 Design D1

**Design Description.** Representative engineering drawings for Design D1 are contained in Appendix E. The sandwich panels in this design use material equivalent to AS4/3501-6 in the face sheets and 4 lb./ft.$^3$ Nomex honeycomb core. The skin laminate stacking sequence for this particular design is as "hard" as practical (i.e. as many of the plies as practical are oriented in the principal load carrying directions). A minimum of four ±45° plies are in each face sheet to provide shear capability. To simplify the splicing to adjacent structure, panned-down edges are incorporated to provide a solid laminate for attaching. The edge-reinforcing members consist of AS4/3501-6 fabric draped over an 18 lb./ft.$^3$ Rohacell closed cell foam insert. This insert acts both as an edge close-out and shear load path for transition from sandwich panel to solid laminate. The precured, cobonded J-section frame uses triaxially (2-D) braided material, equivalent to AS4/3501-6.

**Manufacturing Plans.** The skins and splice straps for Design D1 are tow placed. The fabric of the edge-reinforcing members is draped over the Rohacell foam, and left in an uncured state. The triaxial braided preforms of the J-section frames are batch RTMed (2 in a single operation).

The outer skin is placed on the cure tool, followed in order by an adhesive layer, honeycomb core and uncured edge members. An adhesive is used between the honeycomb and Rohacell foam to provide sufficient continuity of the core. Another layer of adhesive is placed on the core prior to location of the inner skin. This assembly of the sandwich panel uses an automated gantry systems for application of the adhesive, and locating the honeycomb, edge members and inner skin. The frames and associated support cure tooling are located onto the inner skin for subsequent cure. This tooling is required to prevent core crush and frame misalignment, which is critical for body-section assembly.

The ramped-edge honeycomb design uses the same major-assembly processes as described for Design C1, except that no stringer splices are required and only one circumferential splice member is required.

**Design Drivers.** The details which most influence this design are (1) eccentric loading caused by skin ply drop-offs shifting the section neutral axis, (2) coefficient of thermal expansion compatibility between the outer and inner skins, and (3) damage tolerance requirements on face sheets.

Consideration of thermal expansion compatibility between inner and outer face sheets is important to avoid panel warping due to residual stresses. Longitudinal and hoop direction coefficients of thermal expansion for the two face sheets are within 20% of each other. Ply drop-offs are also carefully designed to minimize the effect of local bending due to the eccentricities created by a shift in the neutral axis at drop-off locations. Damage tolerance requirements in both the hoop and longitudinal directions account for the critical margins along the entire panel. The sandwich design reduces the local bending stresses at the tip of longitudinally oriented notches, which reduces the penalties for damage tolerance under pressure loads. Buckling is not a critical factor in this design.

The panned-down splice design creates eccentric loading at the joints. At the circumferential joint, the splice fastener at the panel centerline determines the required thickness to resist bolt bearing stresses. A significant number of plies added are in the outer skin, both for more gradual load transfer to the panned-down laminate and to provide sufficient bearing capability for the splice fasteners, including effects of eccentricities.

The longitudinal joints also use a panned-down edge reinforcing insert. The important issues for this splice are similar to those for the circumferential splice. Additional plies in the outer skin, extending about 14" from the edge, provide sufficient thickness to allow for the countersunk frame splice fasteners.

Frames are designed to resist the bending loads associated with the ULTIMATE load condition. The sandwich panel adds significant capability to this bending load resistance, resulting in relatively small frame members. Again, tension in the inner frame flange is the critical stress which sizes much of the frame laminate. The frame splice member is also designed to resist these loads.

**Cost/Weight Results.** The results of the study show that this design concept is 98% of the cost of 767-X baseline concept and 64% of the weight.

Division of weight between the various portions of the structure is illustrated in Figure 5-18. The skin (including core) contains nearly all of the weight, since the stringers are eliminated and the sandwich construction reduces the frame-stiffness requirements, and therefore their weight.

The relationship between recurring and nonrecurring costs for this design family are shown in Figure 5-19. The relationships are very similar to those for Designs B1, B2, C1, and C2. The recurring fabrication, however, is somewhat higher and the recurring material is somewhat lower for Design D1.

In Figure 5-20, recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. The recurring cost breakdown is similar to Designs C1 and C2, reflecting the use of bonded frames in both designs. The non-recurring cost breakdown is comparable to those of Designs B1, B2, and C1, with approximately half these costs for fabrication and the other half for bonding and assembly/installation.

Recurring material and labor costs for each major manufacturing step are shown in Figure 5-21. Skin and frame fabrication, and panel bonding remain significant cost centers for the sandwich designs. The panel bonding costs are approximately equal to

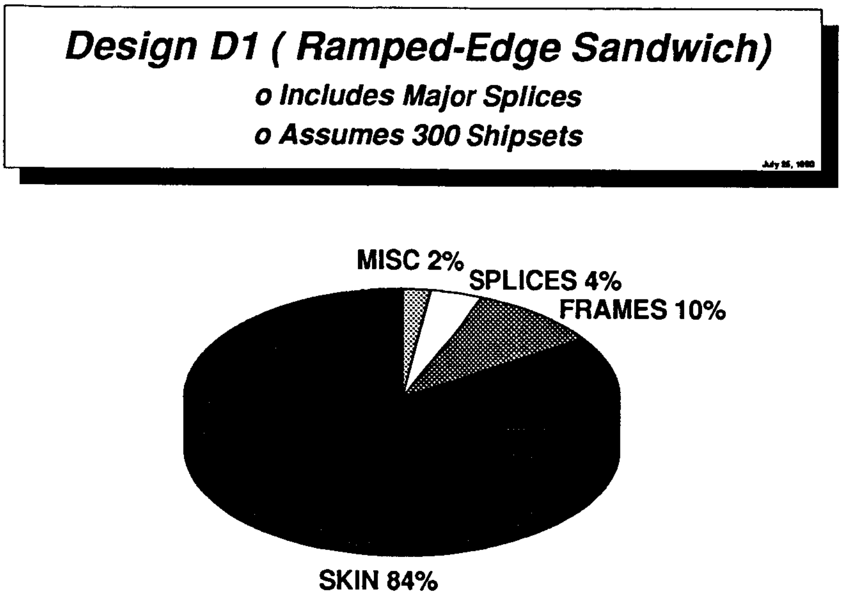



Figure 5-18: Weight Breakdown of Design D1

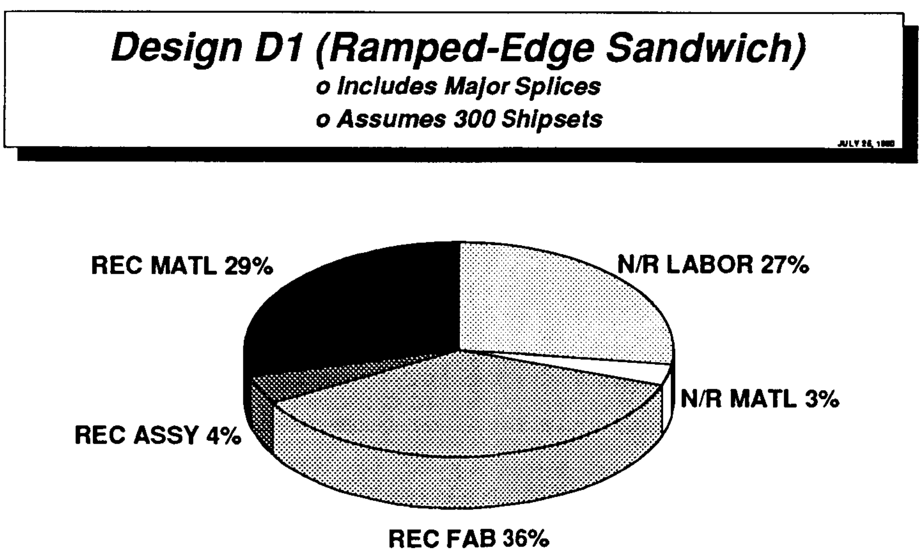



Figure 5-19: Recurring and Non-recurring Costs of Design D1

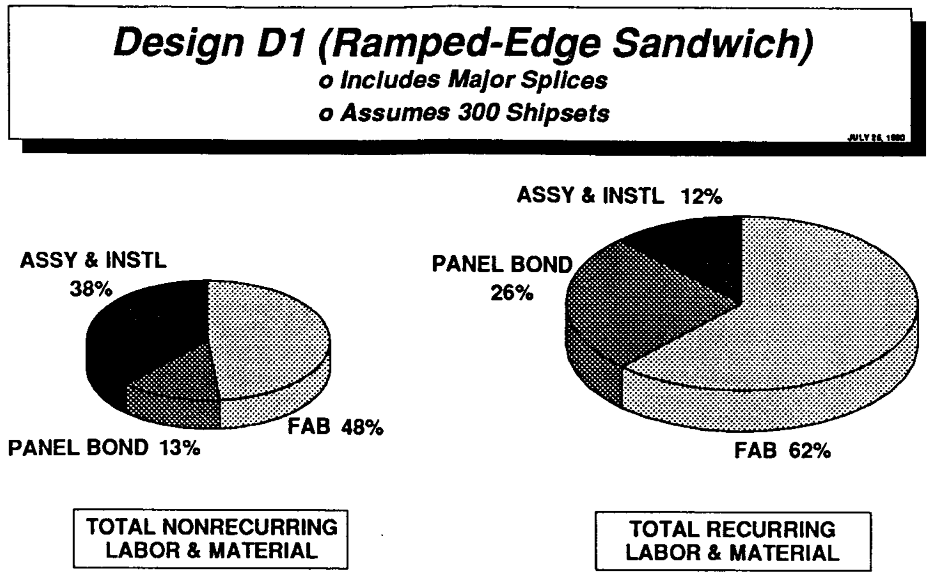



Figure 5-20: Breakdown of Recurring and Non-recurring Costs of Design D1

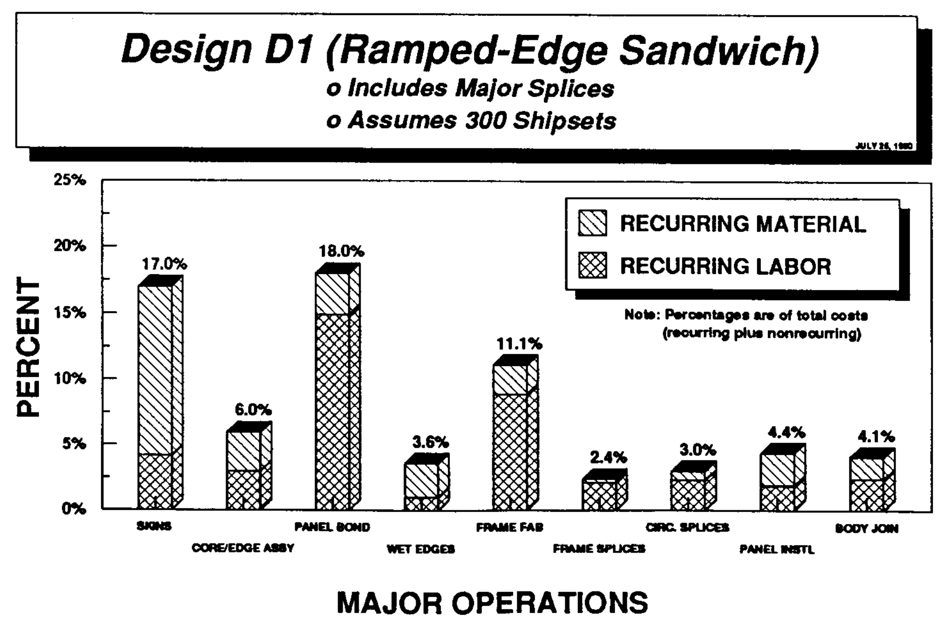



Figure 5-21: Recurring Costs by Major Operation of Design D1

the skin costs, a relationship that is also displayed by bonded-frame skin/stringer designs (i.e., Designs C1 and C2).

### 5.2.6 Design D2

**Design Description.** Representative engineering drawings for Design D2 are contained in Appendix F. The sandwich panels in this design use IM6/3501-6 material in the face sheets and 4 lb./ft.$^3$ Nomex honeycomb core. A soft face-sheet design (i.e. at least 50% angle plies) is employed to minimize ply drop-offs at the panel splices and possibly increase impact damage resistance. This results in very heavy face sheets. A square-edged design replaces the panned-down edge concept used in Design D1. A solid-core strips along the edges of the panel are required to provide adequate strength for fastening and to serve as a close-out edge piece. The J-section frames in this design differ from those in Design D1 only in manufacturing process.

**Manufacturing Plans.** The inner and outer skins, and the required buildups, are tow placed using the quadrant approach discussed in Section 4.1. The J-section frames are fabricated using a dry-fiber curved-pultrusion process. This process requires secondary post-forming for proper curvature control.

The prespliced 4 lb./ft.$^3$ honeycomb core (5 splices) and extruded polyimide edge members are located onto the outer skin. The edge members are secured at the corners with low-cost injection molded snap-in corner pieces. The inner skin is then located onto the core. Adhesive is used between the skins and core to provide an acceptable bond. As in Design D1, an automated gantry system is used for adhesive application and part location. The precured frames and the frame tooling are located in a similar fashion as Design D1.

The square edge honeycomb design uses the same major-assembly processes described in C1. The only differences are that no stringer splices and two circumferential splice straps are required.

**Design Drivers.** The critical design criteria that drive the layup and locations of the face-sheet ply drop-offs are similar to Design D1. Eccentricities due to ply drop-offs create local bending loads, which combine with the in-plane axial and hoop loads. Compatibility of the inner and outer face sheet thermal expansion coefficients determines which plies to drop along the panel length. Buckling of the sandwich panel is not critical for this design.

The square-edged design eliminates much of the eccentric bending encountered at the splice in Design D1. The insert also provides sufficient through-the-thickness strength to react the bolt clamp-up load encountered at the splice. The splice itself consists of an inner and outer splice plate connected to the sandwich with fasteners. The forward circumferential splice requires additional plies in both the inner and outer face sheets to react fastener bearing. The insert is assumed to react only the clamp-up loads, leaving the skins to carry the inplane loads through bearing. The circumferential splice at the more lightly-loaded aft end requires only one additional inner-skin ply to react the bearing loads.

Because of the soft-skin design, sufficient capability is available in the skins at the panel edges to resist the longitudinal splice loads without additional plies.

Tension in the inner frame flange due to the applied loads determines the frame and the frame splice designs.

**Cost/Weight Results.** The results of the study show that this design concept is 115% of the cost of 767-X baseline concept and 80% of the weight.

The division of weight between various portions of the structure is illustrated in Figure 5-22. The percentage of skin weight for this soft-skin/IM6 design concept is less than that of Design D1, despite an increase in actual skin weight. This is due to significantly higher splice and fastener weights from the two splice plates and longer fasteners required by the square-edged design.

The relationship between the recurring and nonrecurring costs for this design family are shown in Figure 5-23. The recurring material appears as a larger portion, and the recurring fabrication a smaller portion, of the total costs than with Design D1. The higher material costs are partially attributed to the IM6/soft-skin combination, which results in a much higher total cost. The lower fabrication costs are due to the unmachined square-edge insert used in this design, as opposed to the machined Rohacell foam ramped-edge insert from Design D1.

In Figure 5-24, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. The recurring fabrication costs appear higher in this design than in Design D1. This is attributable to the high skin costs. The non-recurring cost breakdown are similar to the other designs.

The recurring material and labor costs for each major manufacturing step are shown in Figure 5-25. The skin costs appear much higher than in Design D1. Again, this is due to the combination of the IM6 fibers with the soft-skin design. All other costs, although skewed downward by this high skin cost, appear very similar to those of Design D1.

## 5.3 Analysis of Cost/Weight Results

### 5.3.1 Synopsis

From the design studies conducted, several generalizations can be made concerning design drivers. Tension FAILSAFE damage tolerance controls the majority of the panel in all designs. Stringer thicknesses are determined by Euler stability considerations. Skin and stringer thicknesses at the edges of the panels are controlled by the fastener

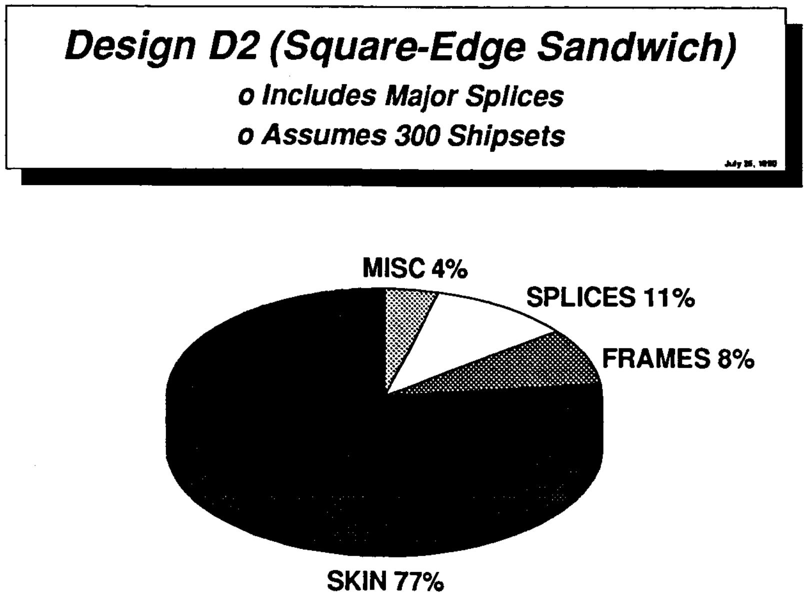



Figure 5-22: Weight Breakdown of Design D2

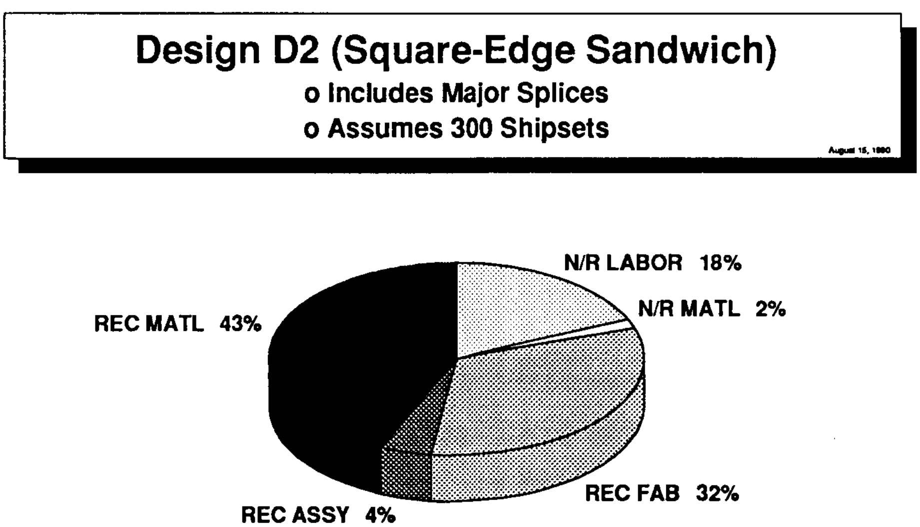



Figure 5-23: Recurring and Non-recurring Costs of Design D2

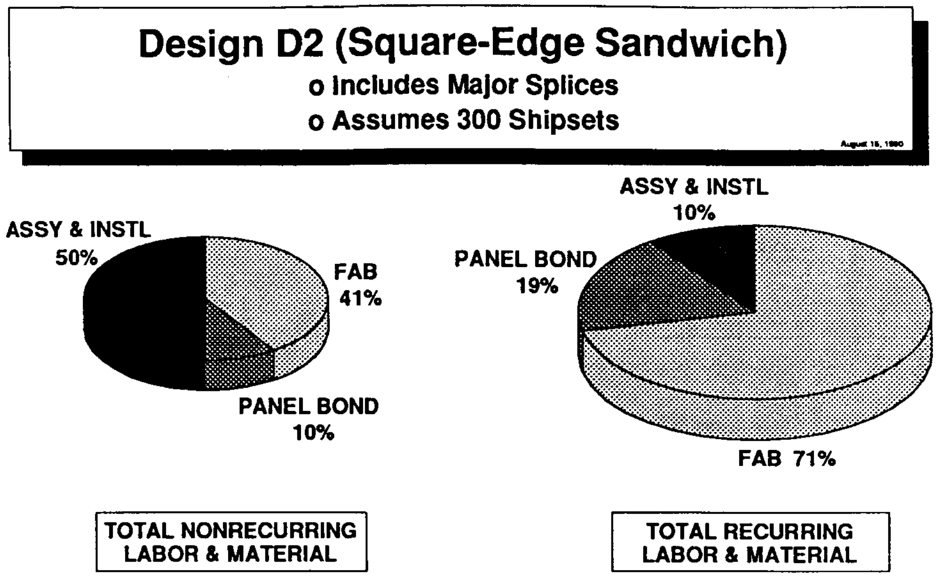



Figure 5-24: Breakdown of Recurring and Non-recurring Costs of Design D2

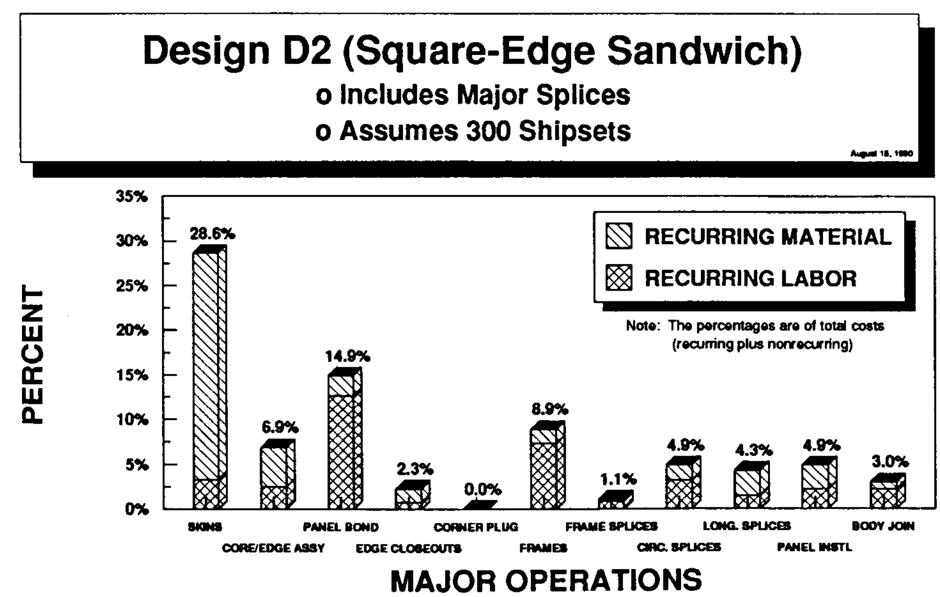



Figure 5-25: Recurring Costs by Major Operation of Design D2

bearing requirements. Minimum gage requirements effect the skin thicknesses near the aft (lightly-loaded) end of the panels.

Figure 5-26 illustrates the approximate weight breakdown encountered in the six design concepts. The stiffened panel (skin and stringers, or sandwich panel) accounts for 70 to 80% of the total crown quadrant weight, with skin in the skin stringer designs responsible for about 50% of the total. Frames account for 10 to 15%, and the splices 5 to 10% of the total.

Some general trends can also be extracted from the cost results. Recurring costs comprise approximately 75% of the total costs, and are divided nearly equally between material and labor. About half of the nonrecurring costs are related to element fabrication (e.g., skins, stringers, frames, etc.), with costs relating to bonding and assembly operations comprising the other half. In contrast, approximately 70% of the recurring costs are related to element fabrication, with the remainder related to bonding and assembly operations. The most significant recurring cost centers are (1) the fabrication of the skin, stringers and frames; (2) the panel bonding operation; and (3) fasteners required for installation.

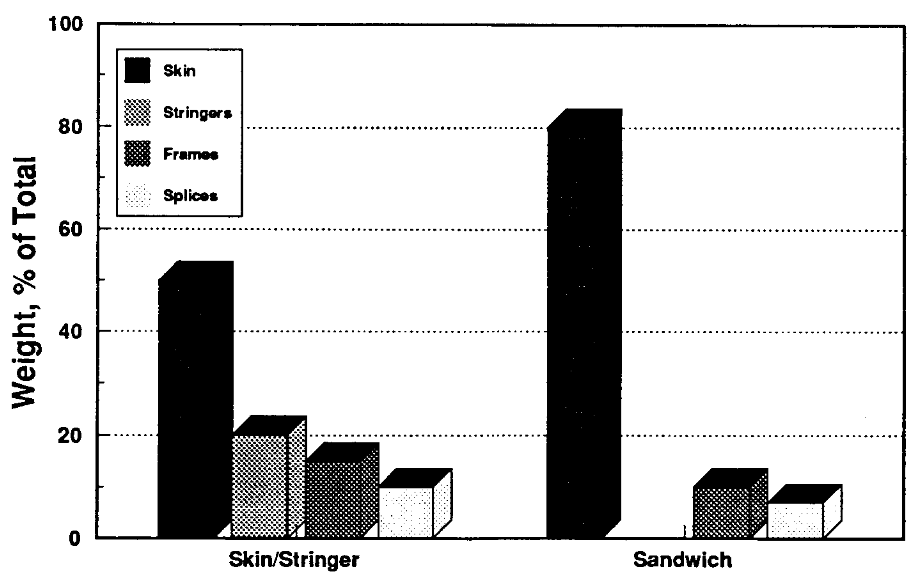



**Figure 5-26: Approximate Weight Breakdown of Crown Designs**

A comparison of the cost/weight results, normalized to that of the 767-X aluminum baseline, is contained in Figure 5-27. The costs are within 100 to 120% of the baseline value. The skin/stringer concept weights are approximately 50 to 60% of the baseline, with the two sandwich concepts (i.e., Designs D1 and D2) being somewhat higher.

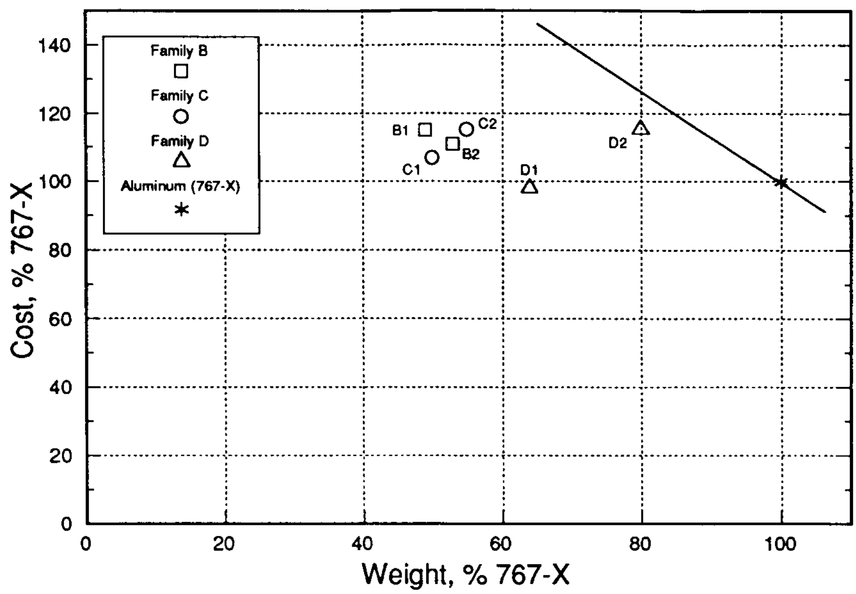



**Figure 5-27: Crown Design Cost/Weight Results**

The sloped line through the 767-X baseline point in Figure 5-27 represents a typical performance value of weight. This value is the amount that customers are willing to pay for reduced weight, and therefore is a measure of the life cycle costs of this weight. All designs falling on a single line parallel to this are of equal value. Those designs falling below this line are more desirable, and those falling above, less desirable. As shown, all composite concepts, although not optimized, are more attractive than the aluminum baseline. Note that Design D2 is less attractive than the other five composite designs.

### 5.3.2 Cost Comparisons

In selecting and developing design concepts in the global optimization process, cost-minimization was a major consideration. In addition, a range of concepts for each element (i.e., skins, stringers, frames) was included within and across the design families to isolate costs.

**Fibers.** One of the primary variables for which costs can be isolated is fiber system. In all designs, either AS4/3501-6 or IM6/3501-6 material was used for the skins and stringers. The analysis of the cost of these fiber systems is shown in Figure 5-28. The bars in this graph show the ratio of AS4 to IM6, with the adjacent bars addressing the behavior observed in the skins and the stringers. The lower performance of the AS4 fiber system results in a 10 to 15% weight penalty due to added material. However, the cost per pound of the AS4 is significantly lower, ranging from 55 to 65%, depending on the material form (i.e., tow or tape). The final cost ratio is the product of these two values, and is in the 70% range. This analysis indicates that, for these applications, the cost advantages of AS4 clearly outweigh its performance penalty. A performance value of weight in excess of $130/lb. would be required to select the IM6 system, significantly higher than normal values.

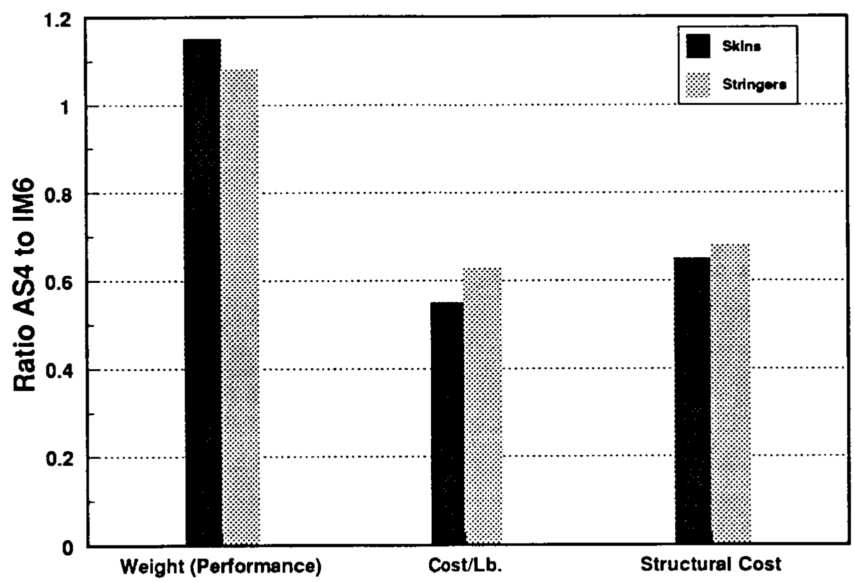



**Figure 5-28: Comparison of AS4 and IM6 Fiber Systems**

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

**Stringers.** A comparison of stringer fabrication processes is contained in Figure 5-29, which illustrates the costs per pound of each stringer design. The pultrusion process used on the Design B2 blade stringers results in cost of $175/lb. primarily due to the cost of the prekitted prepreg material form. The hot-drape-formed hat stringers of Designs B1, C1, and C2, are less costly on a per pound basis (≈ $110/lb.), although recurring labor was higher than the pultrusion process. In a modified Design B1, where AS4 material is substituted for IM6 (including additional plies to meet the performance requirements), the cost per pound is reduced to approximately $75/lb.

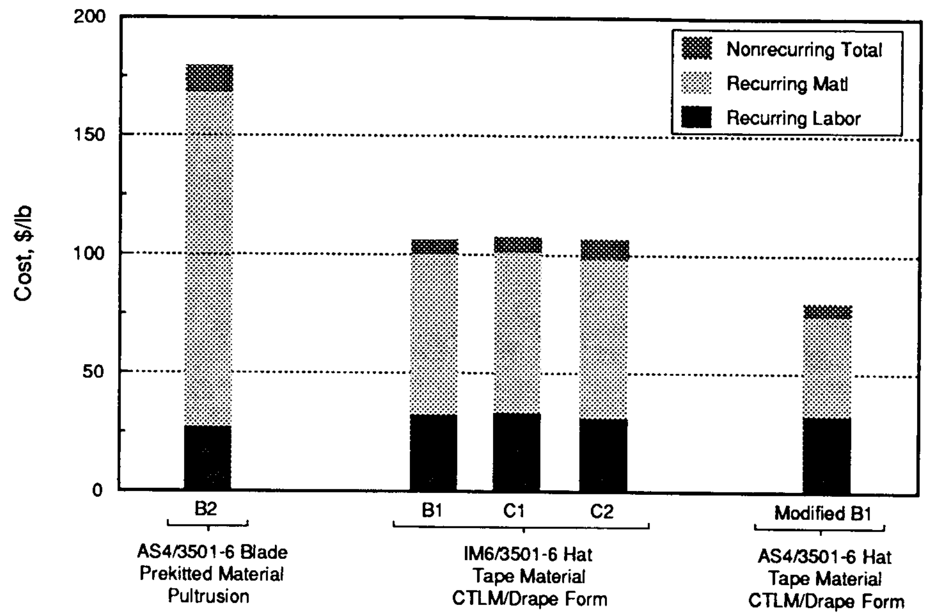



**Figure 5-29: Cost Comparison of Stringer Fabrication Processes**

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

**Frames.** The frame manufacturing process used for each design is the primary variable for which costs can be isolated. Costs per pound are shown in Figure 5-30. The compression-molded fabric (Design B1) resulted in the highest cost ($170/lb). High recurring labor and material costs for the compression-molded fabric frame are due to hand layup of the laminate charges and the use of a fabric prepreg material, respectively. The costs per pound of batch processed braided/RTM frames exhibited a considerable range. This is attributed to the number of frames in a batch process, with the costs reducing from $160/lb to $90/lb as the quantity of frames fabricated in a single operation increase from 2 to 16. The $116/lb cost of the thermoplastic concept (Design C2) is lower than all other concepts, except the 16-at-a-time batch RTM process (Design C1). A breakdown comparison of the C1 and C2 frame concepts shows the former to have a lower material cost, while the latter has lower recurring labor and nonrecurring costs.

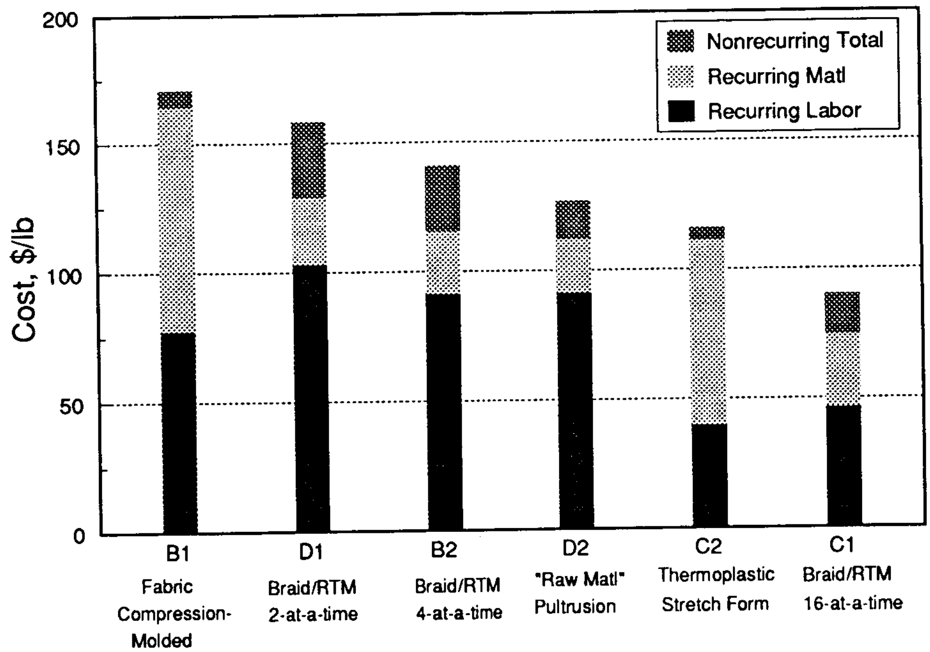



**Figure 5-30: Cost Comparison of Frame Fabrication Processes**

### 5.3.3 Global Optimization

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

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

The results of the study show that this design concept is 98% of the cost of 767-X baseline concept and 54% of the weight.

The division of weight between various portions of the structure is illustrated in Figure 5-31. Very little difference from Designs B1 and B2 is observed in the relative distribution of weight.

The relationship between the recurring and nonrecurring costs for this design family are shown in Figure 5-32. The recurring material is a smaller portion, and the non-recurring costs a larger portion, of the total costs than with Designs B1 and B2. This is a result of lowering the overall material costs by using drape formed stringers and the AS4 material system.

In Figure 5-33, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. A reduction in the recurring fabrication costs, when compared to Designs B1 and B2, is due to the reduced material costs. This results in bonding and assembly/installation costs becoming a greater portion of the total.

Recurring material and labor costs for each major manufacturing step are shown in Figure 5-34. The skin, stringer, and frame fabrication, and the panel bond operation still are the dominant costs, but less so than in either Design B1 or B2. The recurring material costs in the frame assembly, panel installation, and body join operations are primarily fastener costs. As these assembly and installation costs become a larger portion of the total, the fastener costs become significant.

**Family C.** The globally optimized Family C design is a slight modification of the continuously-bonded frame concept of Design C1. The skin, stringer, and associated splice materials are converted to AS4/3501-6, with 2 plies and 1 ply being added to the skin and stringers, respectively, for damage tolerance requirements. The J-section frame with the contoured outer flange is maintained without modification, since it already assumes an RTM batch process of 16 at-a-time.

The results of the study show that this design concept is 99% of the cost of 767-X baseline concept and 55% of the weight, nearly identical to those for the globally optimized Family B design.

The division of weight between various portions of the structure is illustrated in Figure 5-35. The relative weight relationships are nearly identical to those of Design C1.

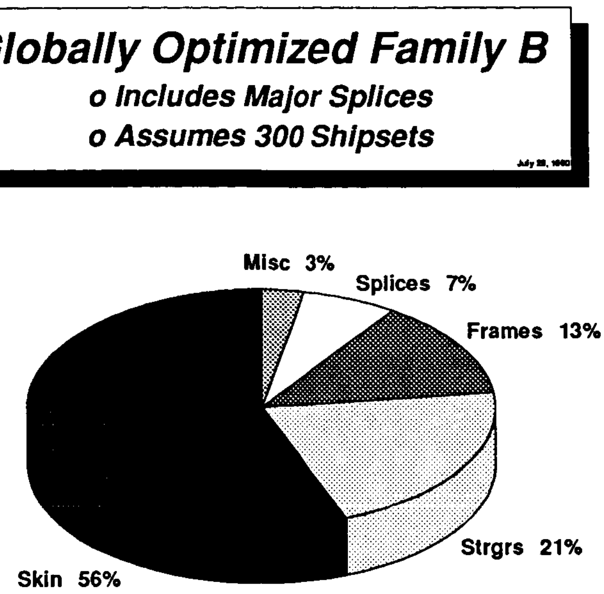



Figure 5-31: Weight Breakdown of Optimized Family B Design

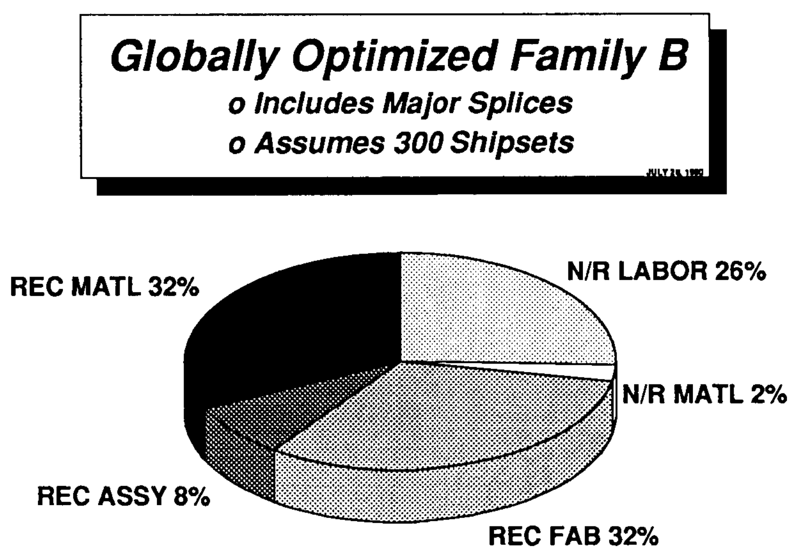



Figure 5-32: Recurring and Non-recurring Costs of Optimized Family B Design

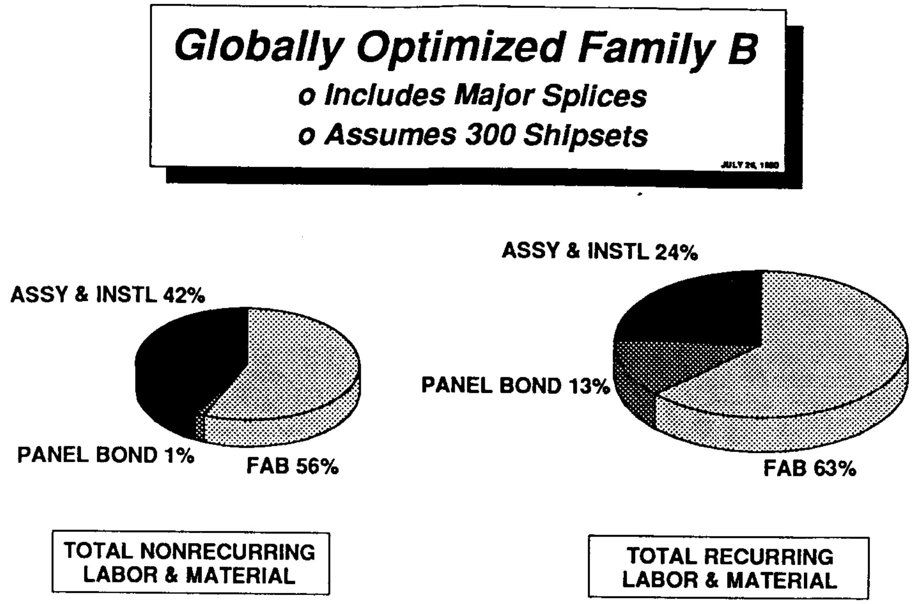



Figure 5-33: Breakdown of Recurring and Non-recurring Costs of Optimized Family B Design

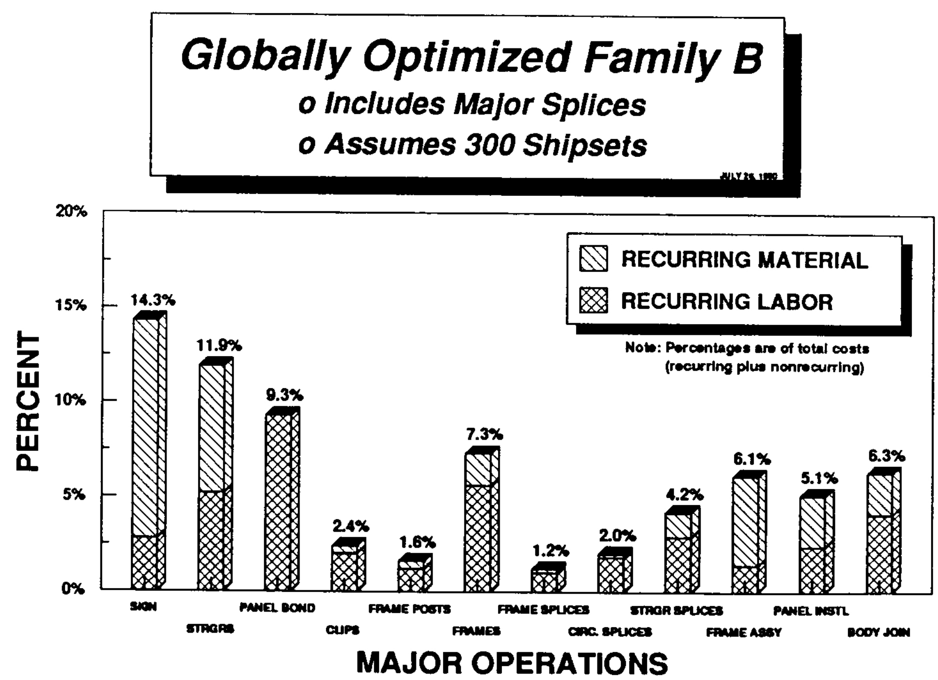



Figure 5-34: Recurring Costs by Major Operation of Optimized Family B Design

The relationship between recurring and nonrecurring costs for globally optimized Family C are shown in Figure 5-36. These relationships are more similar to those of Design C1 than Design C2, since the LDF® frames are not used. When compared with Design C1, however, the recurring material costs are reduced through the use of the AS4 fiber system in the skins and stringers. The other costs, therefore, are a larger portion of the total.

In Figure 5-37, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. These relationships are again very similar to those of Design C1, with recurring fabrication costs reduced due to the use of AS4.

Recurring material and labor costs for each major manufacturing step are shown in Figure 5-38. While skin, stringer and frame fabrication are still major cost centers, panel bonding is the largest cost center, again due to the AS4 system used in skins and stringers. Fastener costs do not appear as large as in the globally optimized Family B design since the frames are not mechanically fastened to the skin.

**Family D.** The globally optimized Family D design is close to that of Design D1. The only modification is the cost-efficient frame batch process that RTMs 16 at a time. The skins are a hard AS4/3501-6 concept. The ramped edge of the quadrant panel is maintained, although it has not been established as clearly superior to the square-edge design.

The results of the study show that this design concept is 94% of the cost of 767-X baseline concept and 64% of the weight.

The division of weight between the various portions of the structure is illustrated in Figure 5-39. These relationships are identical to those of Design D1.

The relationship between the recurring and nonrecurring costs for this design family are shown in Figure 5-40. The results here appear nearly identical to those of Design D1. This is expected since only the frame fabrication costs differ between the two designs.

In Figure 5-41, the recurring and nonrecurring costs are each separated into fabrication, panel bonding, and assembly/installation costs. These costs, again, are nearly identical to Design D1.

The recurring material and labor costs for each major manufacturing step are shown in Figure 5-42. These relationships are also very similar to Design D1. The recurring cost of the fasteners appear to be similar to the globally optimized Family C design.

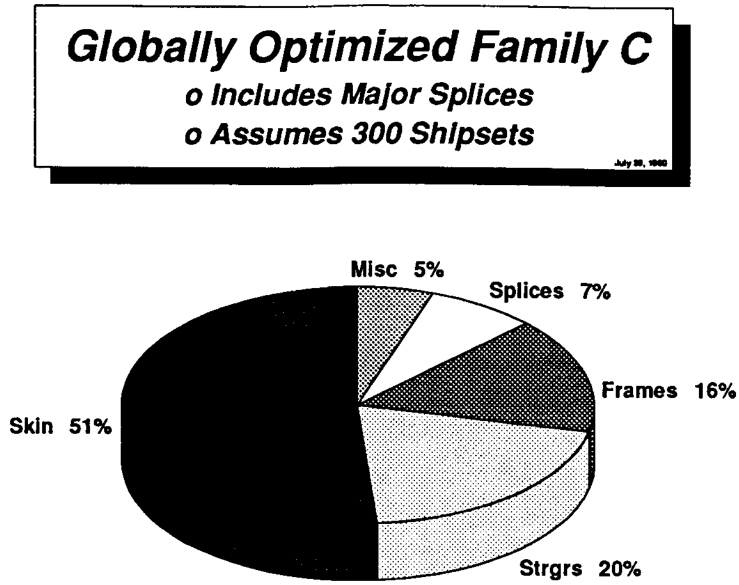



Figure 5-35: Weight Breakdown of Optimized Family C Design

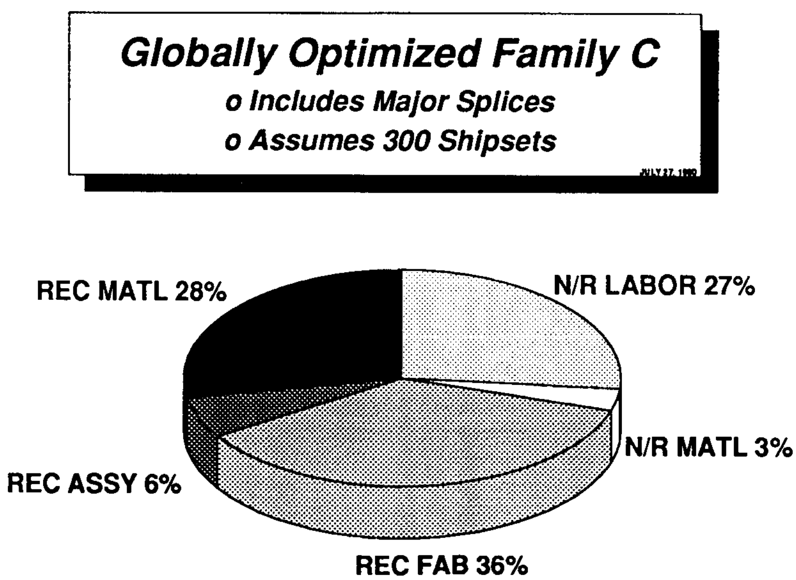



Figure 5-36: Recurring and Non-recurring Costs of Optimized Family C Design

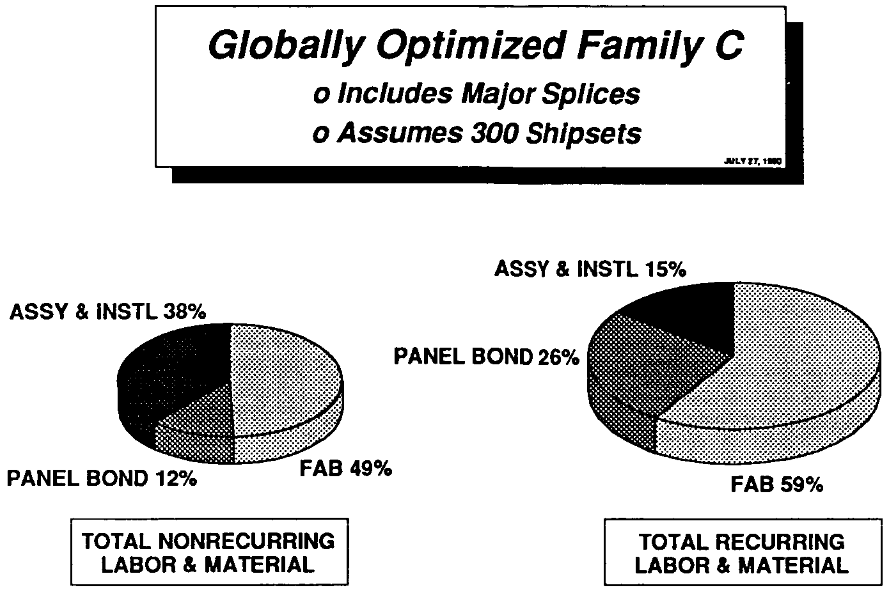



**Figure 5-37: Breakdown of Recurring and Non-recurring Costs of Optimized Family C Design**

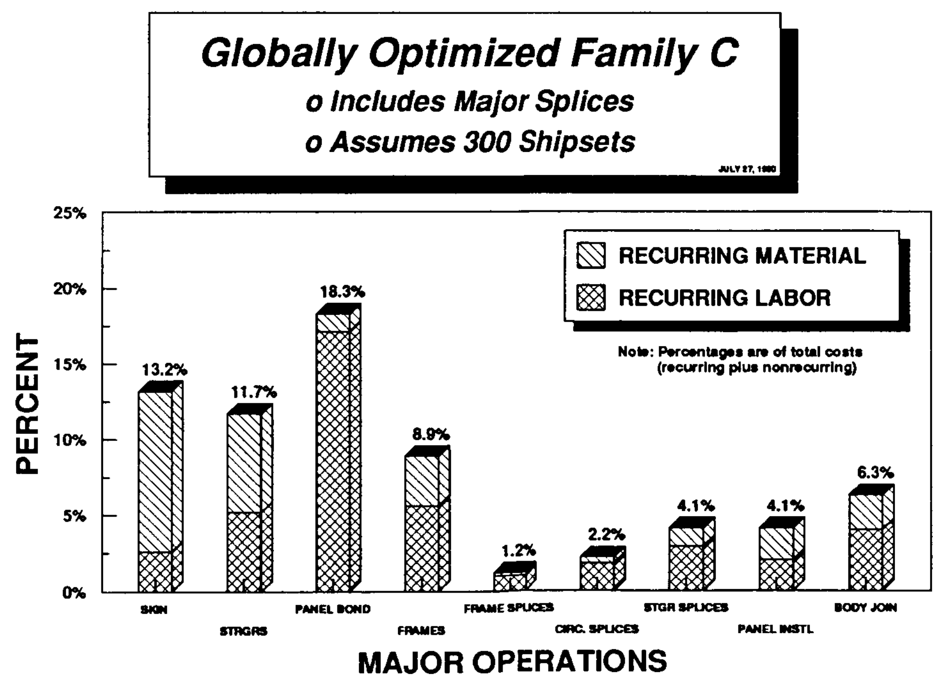



**Figure 5-38: Recurring Costs by Major Operation of Optimized Family C Design**

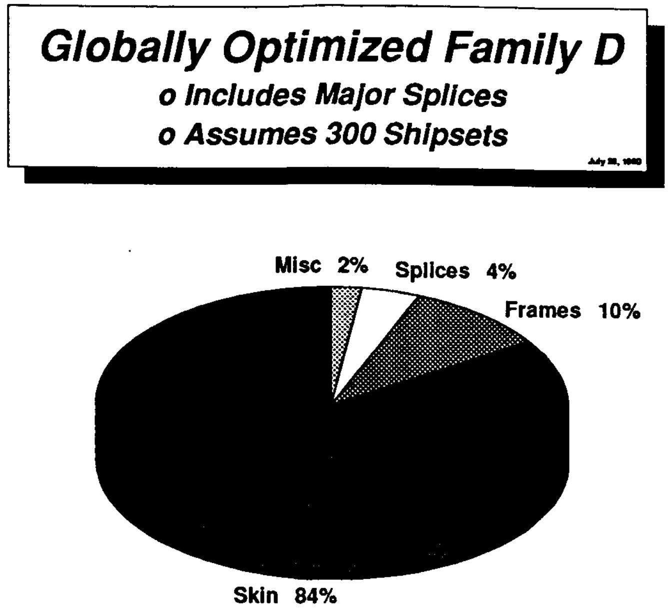



Figure 5-39: Weight Breakdown of Optimized Family D Design

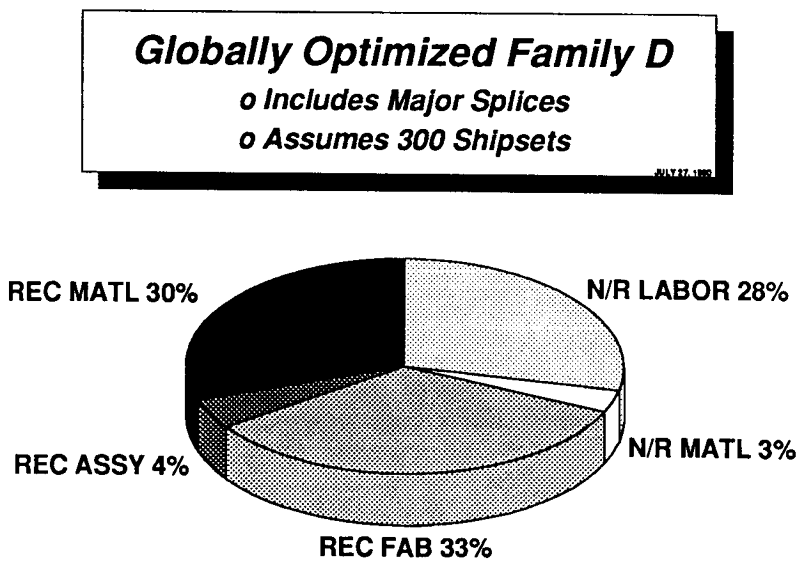



Figure 5-40: Recurring and Non-recurring Costs of Optimized Family D Design

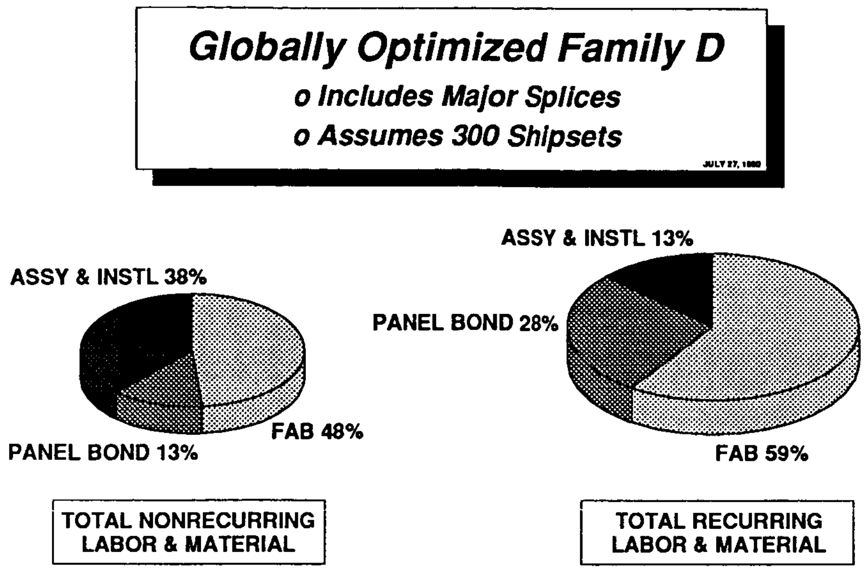



**Figure 5-41: Breakdown of Recurring and Non-recurring Costs of Optimized Family D Design**

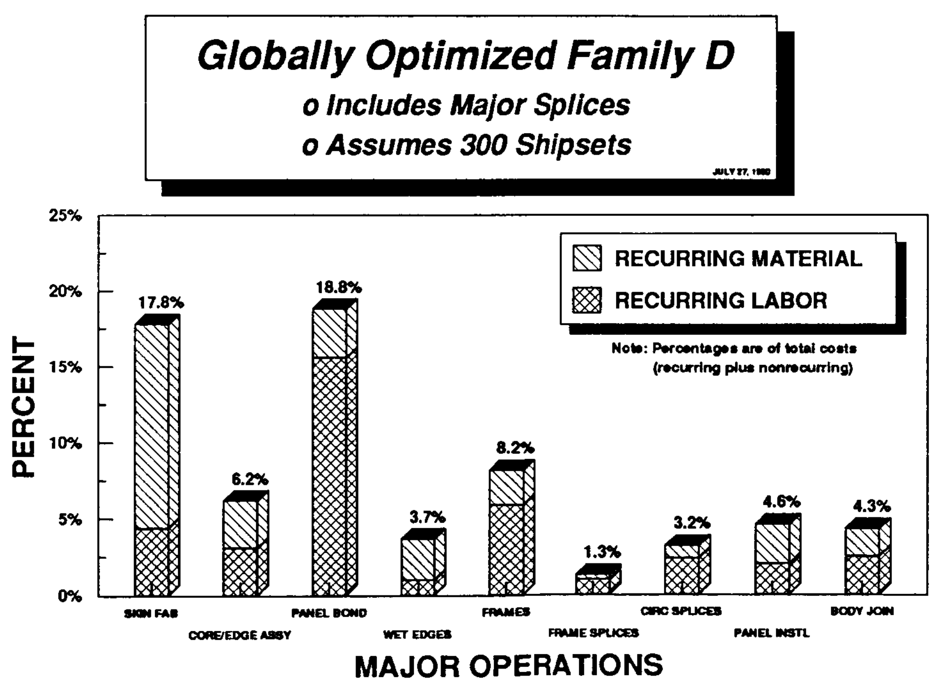



**Figure 5-42: Recurring Costs by Major Operation of Optimized Family D Design**

### 5.3.4 Selection Rationale

The cost and weight results of the globally optimized designs for each family are shown in Figure 5-43 with the original results. The Family B and C costs and weights are nearly identical, both being approximately equal in cost and 50% of the weight of the 767-X. The sandwich design (Family D) is slightly less costly, yet significantly heavier than either of Families B or C. The sloped line through the Family B and C designs reflects a typical performance value of weight. When this is considered, Family D is clearly not an optimum design concept.

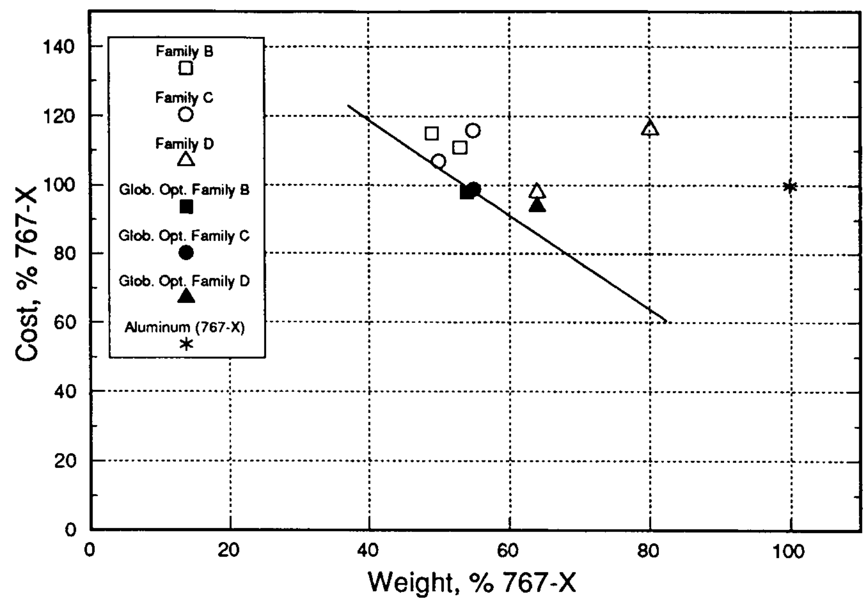



**Figure 5-43: Globally Optimized Designs**

For all concepts, damage tolerance requirements control much of the design. It was therefore a major consideration in choosing the baseline crown concept for further development in local optimization. In all designs, it is assumed, based on limited existing data, that additional skin padding (i.e., tear straps) are not required for tension damage tolerance. Since longitudinally oriented cracks appear to be the more critical condition, the Family B concept seems to be at most risk from this assumption. Families C and D has integrally bonded frame flanges to provide some crack stopping capability, where Family B has no such features.

Family D design appears to be at least risk, since the sandwich construction increases the local bending stiffness at the crack tip, which in turn reduces the localized bending stresses. This is illustrated in Figure 5-44, where analytically derived strength relationships between axially-loaded flat laminates, pressure-loaded curved laminates, and pressure-loaded curved sandwich panels are shown. Significantly higher strengths are realized in sandwich construction for pressure loads and a 8" crack size considered for the FAILSAFE condition.

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

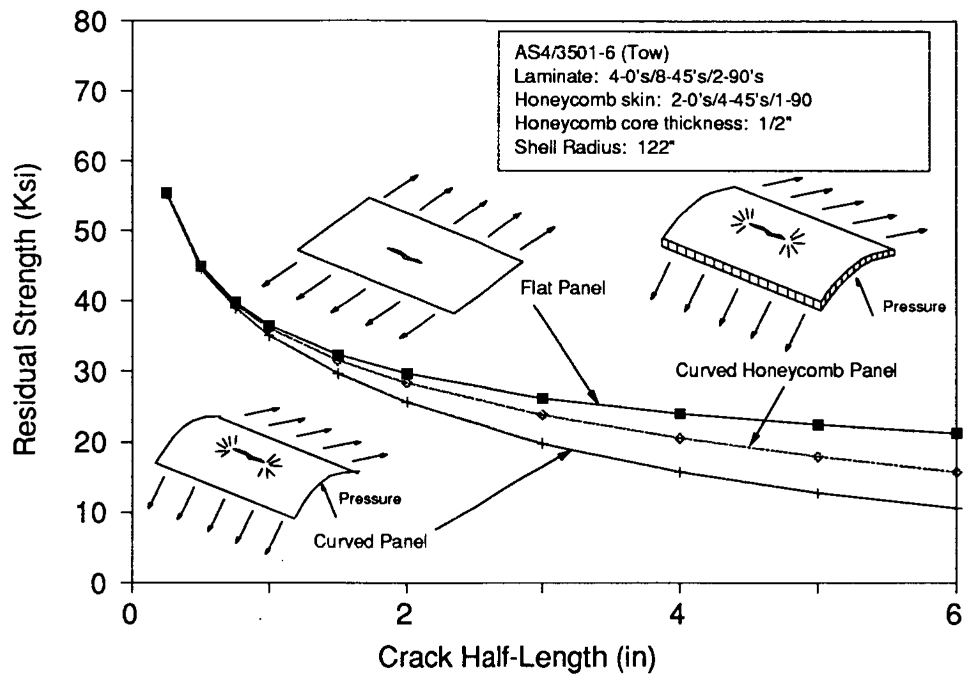



**Figure 5-44: Comparison of Strengths of Damaged Panels Subjected to Pressure Loads**

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

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

### 5.3.5 Local Optimization Potential

The local optimization process provides the opportunity to further refine the selected concept within the cost constraints defined by global optimization. Material, geometric and laminate variables affecting cost and weight are considered in the local optimization, as well as improvements in the manufacturing processes.

Material costs are a major factor in the recurring costs. These costs will be aggressively attacked in the local optimization phase. Less expensive material forms will be considered wherever practical. For example, the stringer charges for drape forming can be tow placed using prepreg tow instead of tape. The use of raw material forms in a stringer pultrusion process will also be evaluated.

The use of less costly materials will be assessed, especially in the skins and stringers, where the majority of material resides. In skins, tensile damage tolerance is the critical property to maintain, while the bending stiffness and tensile damage tolerance are both important in stringers. Fiberglass, which exhibits very large strains-to-failure, appears attractive as a low-cost material for use in tension-damage-tolerance applications. In the skins, for instance, an intraply hybrid consisting of S-glass and AS4 material could provide similar (or even improved) residual strength as compared to an all graphite design. For example, a one-for-one replacement of some graphite would result in a substantial cost reduction, with some weight penalty due to the higher S-glass density. This intraply hybrid concept is also ideally suited for the efficient tow-placement process. Similar concepts could also apply to the stringers. Rough estimates indicate that substituting a 50% S-Glass, 50% AS4 material into the skins and stringers on a ply-for-ply basis would result in a 10% cost reduction and a 10% weight increase for the total crown quadrant, as compared with a non-hybrid AS4 skin and stringer design.

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

Several manufacturing improvements have been itemized that will be investigated. Tow placement efficiency rates can be increased by simply enlarging the current band width or using multiple tow placement heads, as mentioned in Section 4.3.1. These technologies are considered to be low risk and could conceivably increase rates up to 100%. To lower the cost of the splice straps, a large textile knitted full-depth stack could be resin transfer molded and cut into the individual splice straps. This process takes advantage of batch mode processing without significantly adding complexity or risk. Additional cost saving can be realized when using low cost raw material forms (≈ $25/lb.) for pultruded stringer splices. A major cost center is the process for locating and bagging the quadrant assembly for subsequent curing. The technology of form-fit reusable bagging offers significant cost savings by reducing locating tooling, recurring material costs, rejection rate, and assembly/bagging labor.



C-2.

As was illustrated in the cost breakdowns for the optimized families, the recurring fastener purchase costs are a substantial cost center. Composite fasteners and rivets will be evaluated to reduce these costs.

Stringer splicing at the fore and aft ends of the quadrant is also a major concern for Family C. Splice concepts that do not require precise stringer alignment will be studied, as a method of reducing the cost and risk in this area.

An estimate of cost and weight impact of the above issues was made to provide an indication of the possible improvement that can be expected during local optimization. Figure 5-45 shows that range, and the potential improvements in the aluminum baseline design. These aluminum improvements relate primarily to breakthroughs in assembly technology, including high-speed robotic fastening. The broader width of the composite potential is an indication of the wider range of materials and other variables available in the local optimization process. The cost-reduction potential appears to be significantly greater than that for the aluminum baseline.

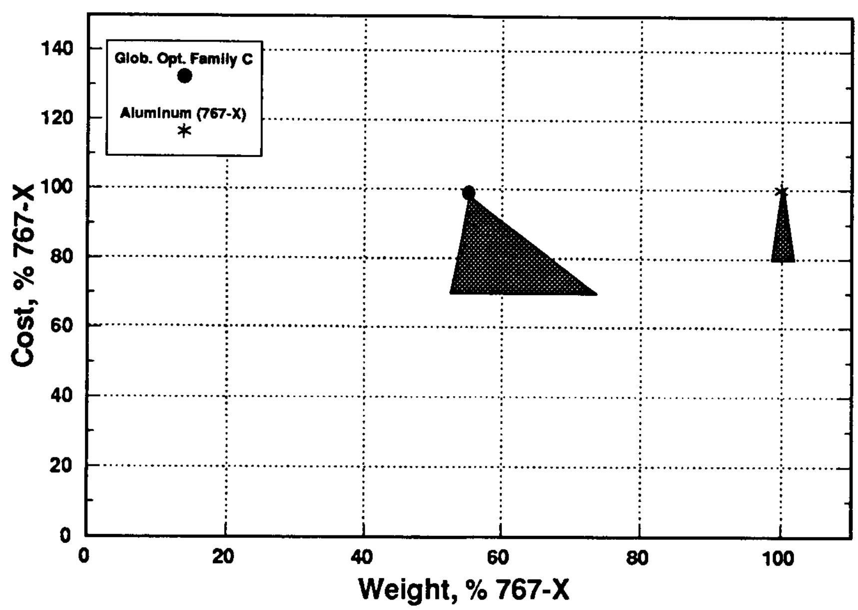



**Figure 5-45: Local Optimization Potential**

# 6.0 CONCLUDING REMARKS

### Design Build Team Approach

The DBT approach used in ATCAS was derived by team members representing manufacturing, structural design, structural analysis, materials, quality control, and cost analysis. Early developments by the ATCAS DBT prompted a need for an efficient method of studying candidate fuselage design concepts and manufacturing processes. Initially, 30 candidate fuselage panel concepts were produced by design personnel. The number of concepts was increased from 30 to 159 during subsequent brainstorming sessions with the full DBT. Schedules would not allow cost and weight evaluations of all concepts. Instead, concepts were classified into eight design families, each having common characteristics from a manufacturing viewpoint. This allowed a more viable DBT approach in which the most cost- and weight-efficient family was selected by evaluating a reduced number of concepts representing chosen families. After identifying the best family for a given application, the cost and weight relationships of variables within that family were analyzed in greater detail.

The three step DBT approach developed in ATCAS is used to select, evaluate, and optimize fuselage concepts. The starting point is selection of baseline concepts as those design and manufacturing ideas having an apparent potential for cost and weight savings, combined with an acceptable risk. In the second step, referred to as global optimization, the cost and weight savings are substantiated by performing trade studies for the baseline and a limited number of alternative concepts. The cost estimating procedure for this effort uses detailed designs and fabrication/assembly plans. Global optimization effectively integrates manufacturing data into the design selection process. The final design step, called local optimization, attacks the cost centers identified during global optimization in attempts to further minimize cost and weight.

The ATCAS program is considering new material forms and manufacturing processes. Lack of sufficient data for these emerging technologies can reduce the accuracy of structural performance and cost predictions made during global optimization. Any uncertainties are noted and influence the decisions made in global optimization; however, the risk in selecting new technologies is minimized during local optimization by allowing sufficient time to perform manufacturing trials, generate data bases, and complete more thorough analysis.

### ATCAS Baseline Concepts

The scheduled completion date for ATCAS baseline concept selection in all areas of the fuselage coincided with the end of global optimization for crown panels. Although design details are simplest in the crown, all baseline decisions benefited from cost and weight trade studies for crown panels. Baseline selection was found to be a crucial design step for the timely identification of associated technical issues. This helped to focus early efforts in manufacturing, structural mechanics, and materials technology.

Four quadrant segments were defined for the baseline fuselage section. The quadrant concept is intended to reduce manufacturing costs in two ways. First, assembly costs are lower due to a reduced number of longitudinal panel splices. Second, the quadrant concept is compatible with an advanced tow placement batch method for processing panel skins in all areas of the fuselage. Crown trade studies projected this method of skin layup to be cost effective.

Differing arc lengths, that minimize material waste of the batch process for advanced tow placing skins, were chosen for the ATCAS fuselage quadrants. Crown and keel quadrants were chosen as 90° and 34° segments, respectively. The relatively small keel arc length was due to a cargo door location. Both side quadrants were 118° segments. The side panel skin layup process required that both right and left sides be tow placed in the same batch.

Design Family C, which consists of a skin panel with bonded stringers and frames, was selected for the crown baseline. Window frame and door design details also led to the choice of Family C for baseline side panels. An innovative thick laminate/sandwich concept, which was a variation of Family D, was selected for the keel panel. This choice was made to avoid anticipated problems with composites in fabricating and splicing a more traditional keel panel design (i.e., skin/stringer with discrete keel chord elements).

Manufacturing and assembly steps were conceived for the baseline concepts. These steps included batch processing elements, quadrant subassembly, panel cure, inspection, and final assembly. The batch process for skins was selected as advanced tow placement using the quadrant approach. Since skins constitute the majority of fuselage weight, tow placement was chosen for advantages such as a projected low-cost material form and efficient ply tailoring. Stringers are batch processed using a contoured tape lamination machine and drape forming. This process is particularly attractive for hat shaped geometries. A work station to batch process textiles with resin transfer molding (RTM) was selected for frames, window belt frames, and intercostals. The RTM/textile approach was found to be efficient for such complex part geometries. A rotisserie tool concept and autoclave were chosen for quadrant subassembly and panel cure/cobonding, respectively. Final assembly of quadrant and section splices was envisioned using automated fastener installation.

The most critical manufacturing issue identified for each baseline concept is the effect of locational tolerances and panel warpage on final assembly. Quadrant panel designs have high local stiffness due to bonded stringers/frames or sandwich construction. If the panel is warped or bonded elements are misaligned, stiff quadrants will be difficult to splice. Studies in ATCAS will address this issue with manufacturing trials, robust joint design development, warpage measurements, splice tests, and analysis support.

Another important manufacturing issue pertains to process control of large quadrant sections to yield panels of acceptable quality. The ATCAS program will study this by producing manufacturing demonstration panels with design details typical of actual quadrants. The effects of defects needs to be understood to avoid adding unnecessary costs to the process. Analysis and experiments will study coupons, elements, and subcomponents machined directly from manufacturing demonstration panels.

Critical structural issues which need to be addressed in support of technology development and verification were also identified for each baseline quadrant. Damage tolerance is expected to be a design driver for the entire fuselage, with different combined load conditions and damage scenarios dominating in each quadrant. For example, pressure damage containment (large penetrations subjected to hoop tension loads) dominates the minimum gage crown design and impact damage appears to be crucial for the compression/shear loads characteristic of the lower side quadrant. Compression load redistribution is a major issue for the keel baseline design where cost and weight will be directly related to efficient laminate thickness tailoring. The durability of bonded elements such as frames will need to be studied including the effects of real time, environment, and pressure cycles. Finally, the relationship between material and structural behavior needs to be understood for the unique issues of each quadrant in order to select materials having a minimal cost and adequate performance.

**Crown Quadrant Global Optimization**

Two designs from each of three families were developed for global optimization of the crown quadrant. Each design was sized considering multiple load cases, damage tolerance, and attachment design details. The three families were B (skin-stringer-frame, with bonded stringers), C (skin-stringer-frame, with bonded stringers and frames), and D (sandwich, with bonded frames). A detailed fabrication and assembly plan was developed for each design. These were used to estimate weight, material costs, and labor rates. Both recurring and nonrecurring (minus capital equipment) costs were estimated assuming specified groundrules (e.g., 300 shipsets at a rate of 5 per month).

The two designs and manufacturing plans for each family varied material types, manufacturing processes, and structural variables. This helped to project a range of cost and weight variation for each family. Design trades within a family yielded data on cost centers and variable interactions crucial to local optimization studies. Another advantage of studying two designs per family was that errors in cost estimating tasks (e.g., data entry, plotting) were found and corrected when analyzing differences between design.

All composite crown designs studied were found to be cost and weight competitive relative to the metallic benchmark. Relative weights for composite designs range from 49% to 80% of the metal. The estimated relative costs for composite manufacturing plans range from 98% to 117% of the metal. When considering an economically acceptable cost increase per unit weight savings, all composite designs show an advantage over the metal baseline. One of the six composite designs are clearly not cost and weight competitive with the other five.

The majority of weight for all designs is in the skin, where tension FAILSAFE damage tolerance drives the thickness and layup for most of the crown panel area. Minimum-skin-gage hail impact requirements also control the design of the aft end of some panels. Stringer thicknesses are driven by reversed load stability requirements. Both skin and stringer gages near panel edges are controlled by joint bearing requirements.

Estimates for all designs studied showed that recurring costs are approximately three fourths of the total costs. The most significant recurring cost centers were found to be skin, stringer, and frame fabrication; panel bonding (i.e., element subassembly, bagging and cure); and fasteners required for quadrant assembly and body join. The material and labor parts of total recurring costs are nearly equivalent; however, these two components vary widely for individual fabrication and assembly steps. For example, panel bonding is nearly all labor costs, while batch tow placement processing of skins is dominated by material costs. The breakdown of cost estimates to this and lower levels of detail appear necessary in order to attack cost centers in local optimization.

Relatively high composite material costs are expected to lead to relationships between cost and weight that differ from those of metals. The relatively low aluminum costs generally allow an effective trade of added weight for reduced labor. Such trades may also exist for complex composite element geometries such as frames in which labor is found to be a high percentage of recurring costs. When material costs dominate the process step (e.g., skin tow placement) the opposite is true. Since skin dominates total panel weight, studies to minimize ply count will significantly reduce total costs for a given material type. This was apparent in cost and weight analyses where the heaviest composite crown skins also tended to have the highest cost.

It is important to point out that although cost and weight appear coupled for skins consisting of a given material type, the switch to a high performance fiber to reduce skin weight was not found to be cost effective. This relates to the trade between a higher material purchase price and the costs saved from added performance capability. The economically acceptable increase in cost per unit weight savings was considered in this evaluation. Material cost and weight design trades such as performed in this crown study appear useful in determining an acceptable increase in material cost per added performance. Note that these relationships are likely to be application specific due to differences in design drivers.

Cost and weight comparisons were made between the various materials and process methods used for skin, stringer, and frame elements. Element fabrication costs tended to relate to the complexity of element geometry. In addition, the lowest cost process was found to change depending on element type. The advanced tow placement batch process for simple skin geometry yielded relatively low costs per unit weight in comparison to the best processes found for more complex stringer and frame geometries. When considering stringers, contoured tape lamination and batch drape forming was found to be the most cost efficient of processes studied. The frames were found to be the most complex and had the highest costs per unit weight; however, costs were minimized for these elements with a batch RTM process of braided preforms.

Design concepts for each family studied were globally optimized by mixing and matching the best features. The most promising family was selected based on results from this exercise, and an evaluation of the potential for further cost and weight optimization was conducted. All globally optimized designs used the lower-cost fiber, which was found to have superior cost/weight performance than one having higher structural performance. The most cost-effective processes studied for each element type were also chosen for the optimum concept. Globally optimized Families B and C were both found to be nearly equivalent in cost and weight. Relative cost and weight comparisons with the metal benchmark showed the composite concepts to be 100% of the cost and 50% of the weight. Family D yielded a lower cost with some weight penalty (i.e., 94% of the cost and 64% of the weight of metal). The weight increase for Family D was not found to justify the cost savings. Family C was chosen over Family B, despite greater manufacturing risks, due to good local optimization potential and bonded frames which may help pressure damage containment.

Local optimization is planned to further refine Family C and attack cost centers identified in global optimization. Attempts to reduce material costs will include studies with graphite/fiberglass hybrids, and the use of tow rather than tape for stringers. A software design tool that includes cost and mechanics constraints for crown panels will be used to support optimization of design variables such as stringer spacing, ply orientations, and laminate thickness. The manufacturing approach to panel subassembly and the use of composite fasteners will also be evaluated. A rough estimate of the local optimization potential indicated cost savings up to 25% within the range of acceptable weight penalties. It should be noted that the metallic benchmark may also attain similar cost savings if advanced technologies in automated assembly are adopted.

# 7.0 REFERENCES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4-1 Chang, S. G. and J. W. Mar, "The Catastrophic Failure of Pressurized Graphite/Epoxy Cylinders Initiated by Slits at Various Angles," AIAA Paper #84-0887, Presented at 25th Structures, Structural Dynamics, and Materials Conference, 1984.

4-2 Smith, P. J., L. W. Thomson, and R. D. Wilson, "Development of Pressure Containment and Damage Tolerance Technology for Composite Fuselage Structures in Large Transport Aircraft," NASA CR-3996, August 1986.

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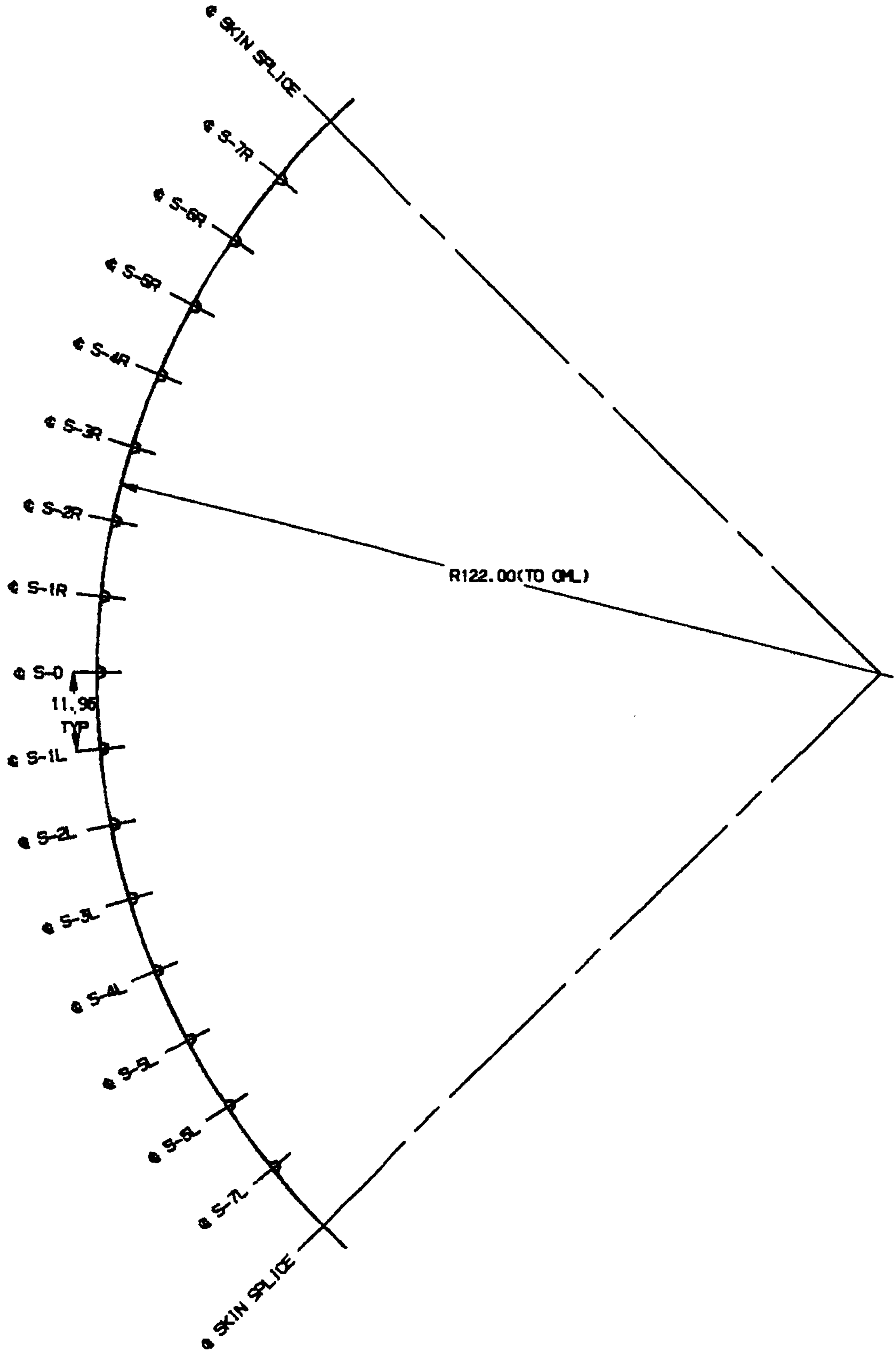
4-6 Friis, E. A., R. S. Lakes, and J. B. Park, "Negative Poisson's Ratio Polymeric and Metallic Materials," J. of Materials Science, 23, 1988, pp. 4406-4414.

5-1 C. C. Poe, "A Unifying Strain Criterion for Fracture of Fiberous Composite Laminates, Engineering Fracture Mechanics, Vol. 17, No. 2, pp. 153-171, 1983.

5-2 Chang, S. G. and J. W. Mar, "The Catastrophic Failure of Pressurized Graphite/Epoxy Cylinders Initiated by Slits at Various Angles", AIAA Paper 84-0887, Submitted at 25th Structures, Structural Dynamics, and Materials Conference, 1984.

# APPENDIX A

# DESIGN B1 DEFINITION



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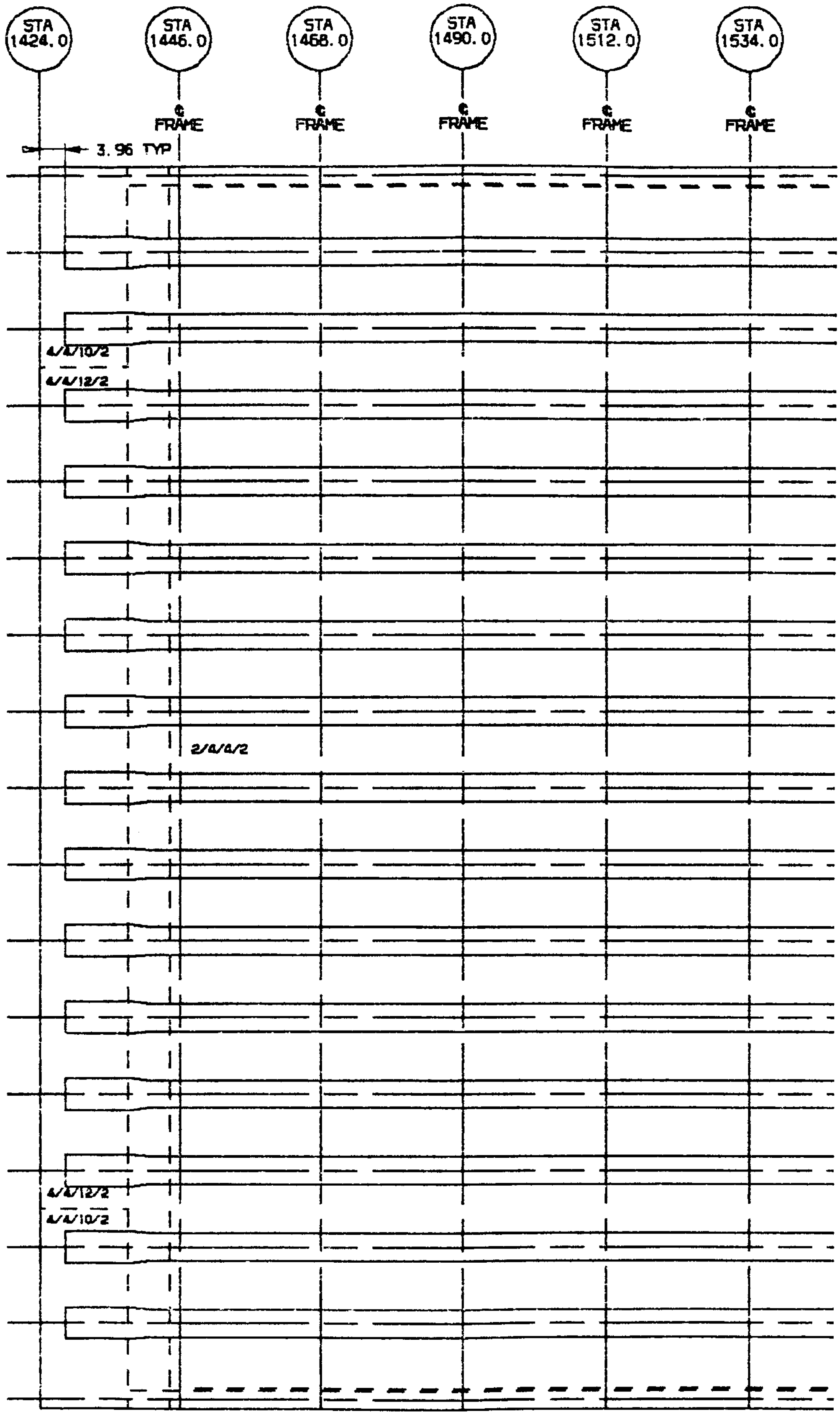
℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
℄ S-2R
℄ S-1R
℄ S-0
11.96
TYP
℄ S-1L
℄ S-2L
℄ S-3L
℄ S-4L
℄ S-5L
℄ S-6L
℄ S-7L
℄ SKIN SPLICE
R122.00(TO OML)


REAR VIEW

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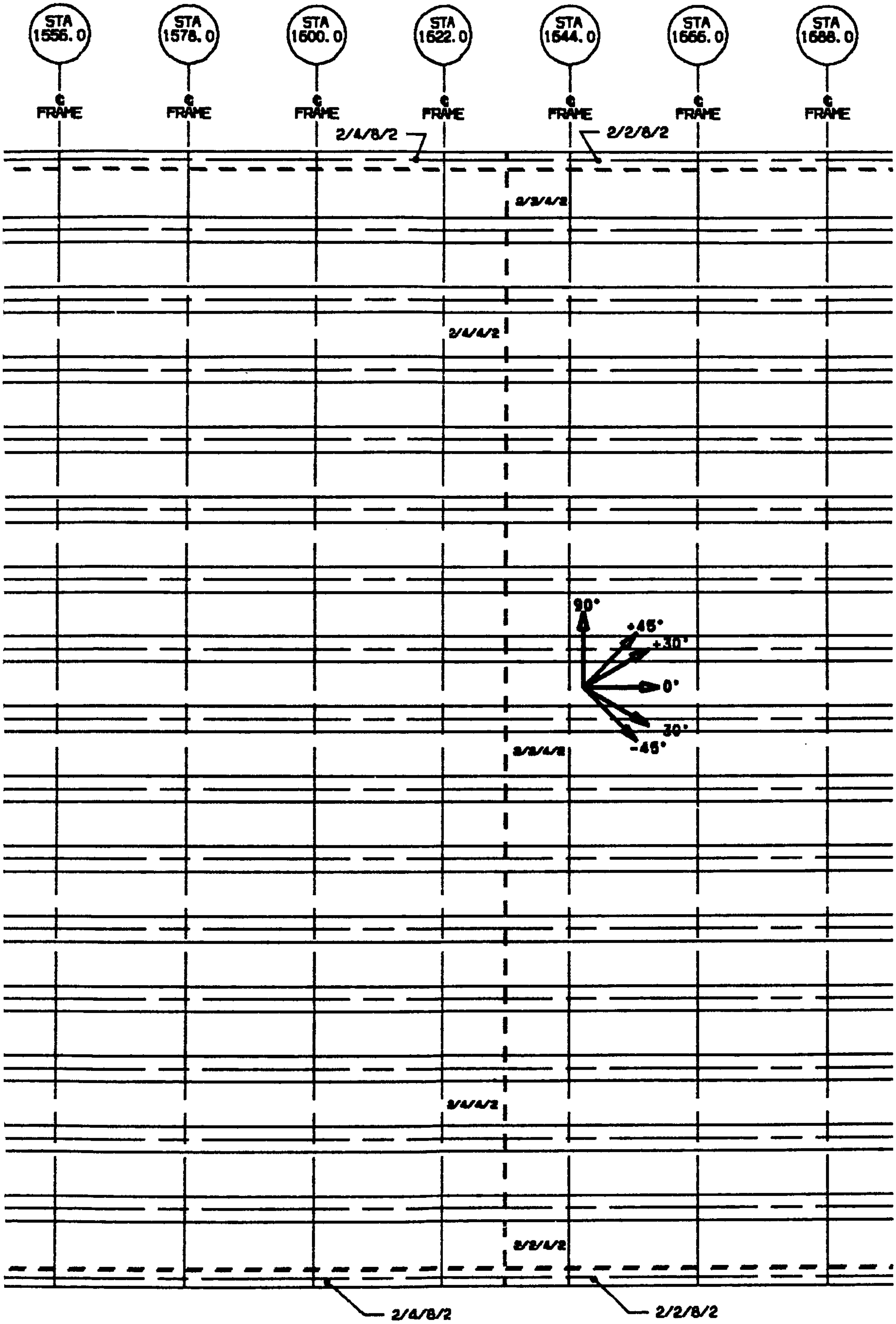

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STA 1622.0
STA 1644.0
STA 1666.0
STA 1688.0
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℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
2/4/8/2
2/2/8/2
2/3/4/2
2/4/4/2
90°
+45°
+30°
0°
30°
-45°
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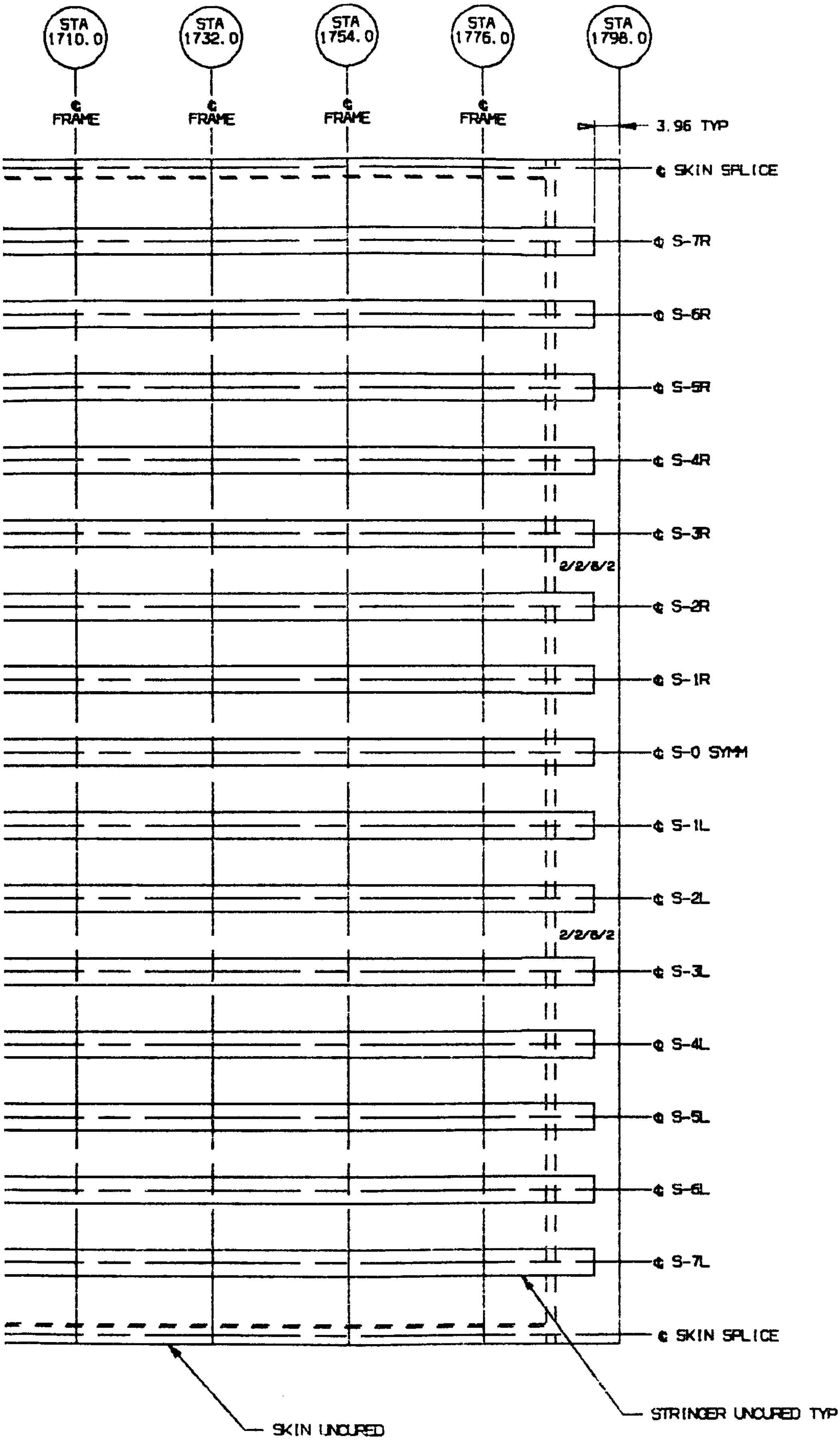
2/2/8/2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STA 1798.0
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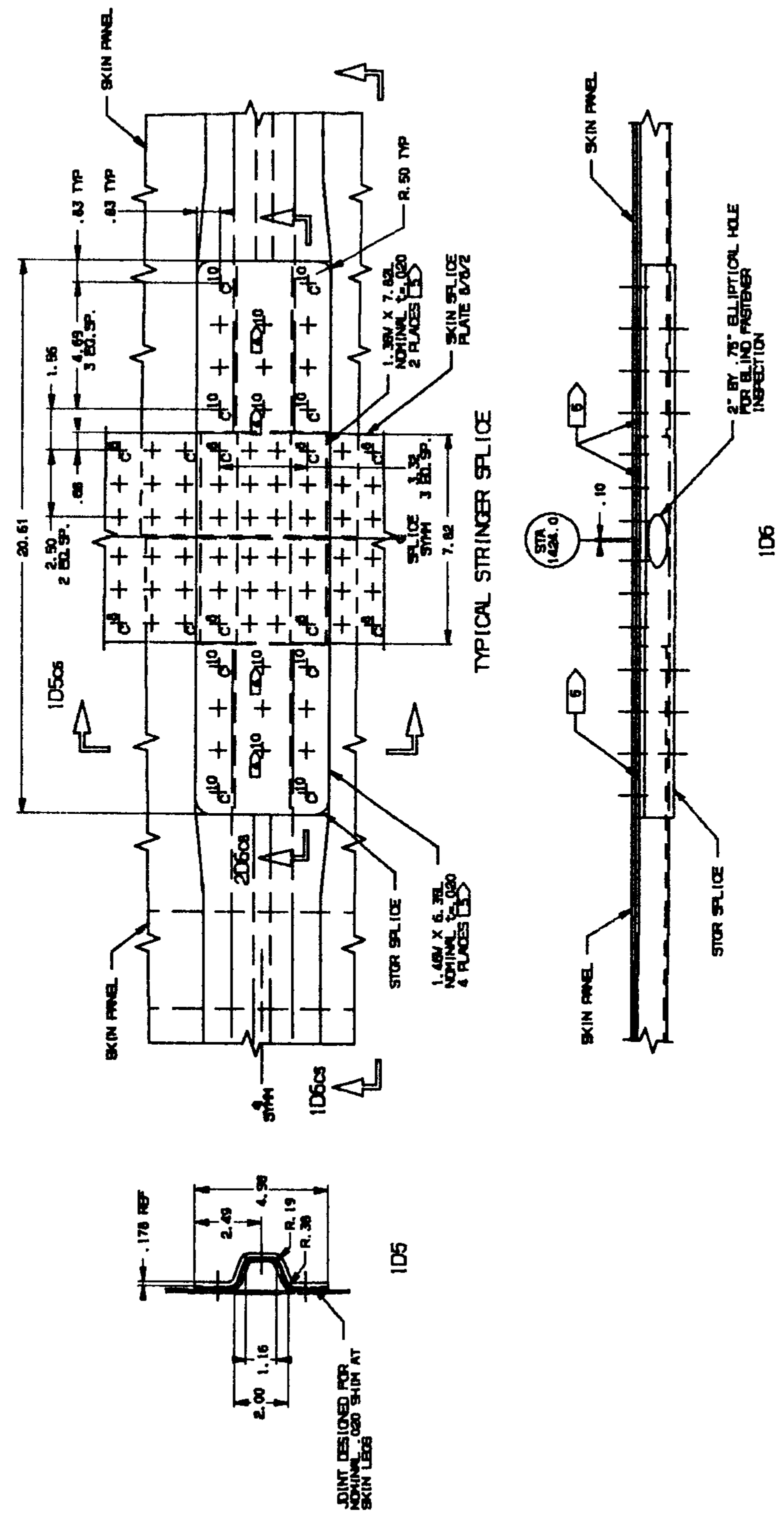
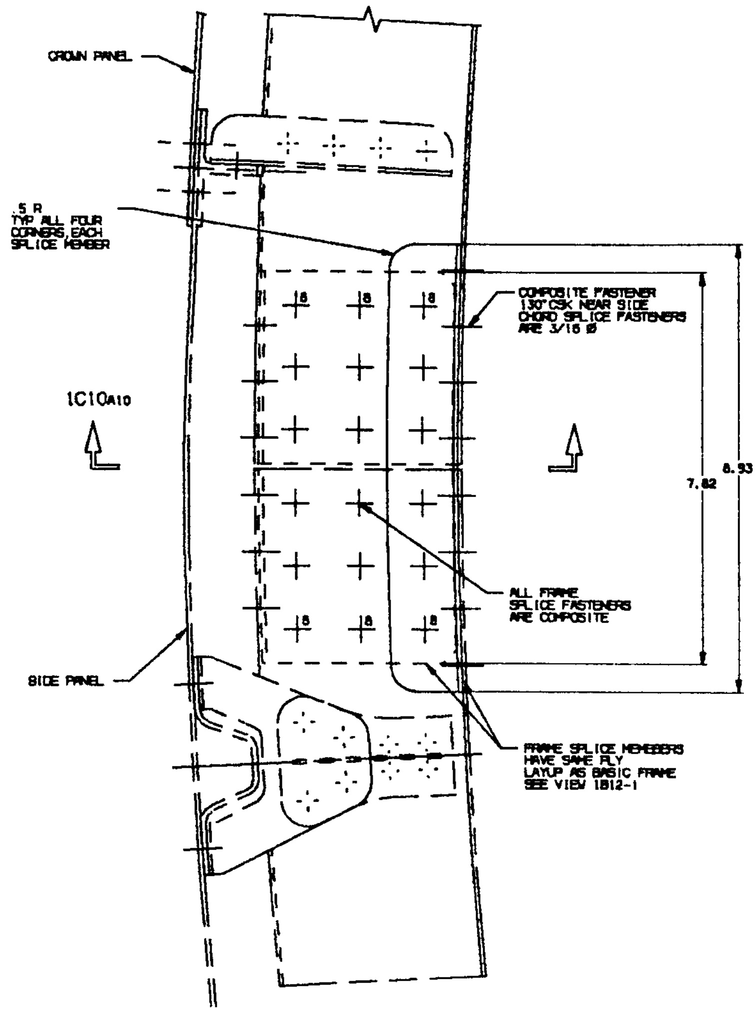
℄ FRAME
℄ FRAME
℄ FRAME
3.96 TYP
℄ SKIN SPLICE
℄ S-7R
℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
2/2/8/2
℄ S-2R
℄ S-1R
℄ S-0 SYMM
℄ S-1L
℄ S-2L
2/2/8/2
℄ S-3L
℄ S-4L
℄ S-5L
℄ S-6L
℄ S-7L
℄ SKIN SPLICE
STRINGER UNCURED TYP
SKIN UNCURED


TYPICAL STRINGER SPLICE
SKIN PANEL
.83 TYP
R.50 TYP
1.56
4.69
3 EQ. SP.
20.61
2.50
2 EQ. SP.
.88
SKIN SPLICE
PLATE 8/6/2
SPLICE SYMM
3 EQ. SP.
7.82
1D5cs
2D6cs
1D6cs
STGR SPLICE
2 PLACES
4 PLACES
STA 1424.0
.10
2" BY .75" ELLIPTICAL HOLE
FOR BLIND FASTENER
INSPECTION
1D6
.178 REF
2.49
4.98
R.19
R.38
1D5
2.00
1.16
JOINT DESIGNED FOR
NOMINAL .020 SHIM AT
SKIN LEGS

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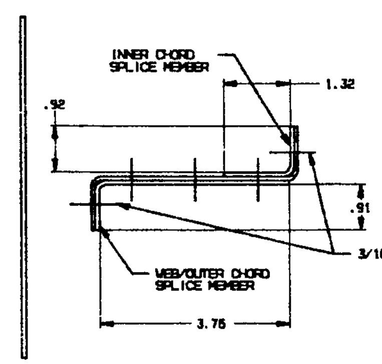
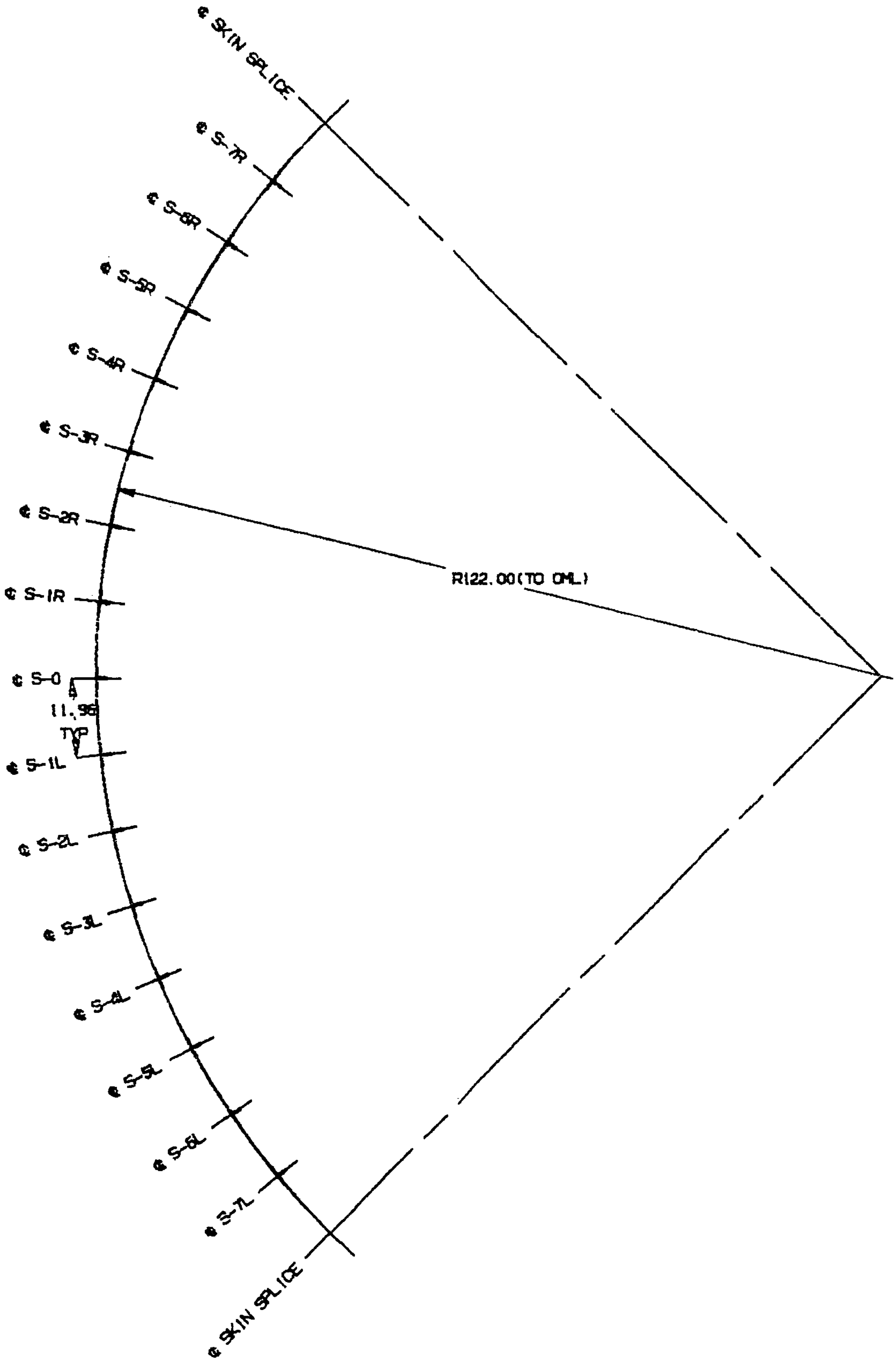



1C10
SCALE: 1/1

# APPENDIX B

# DESIGN B2 DEFINITION



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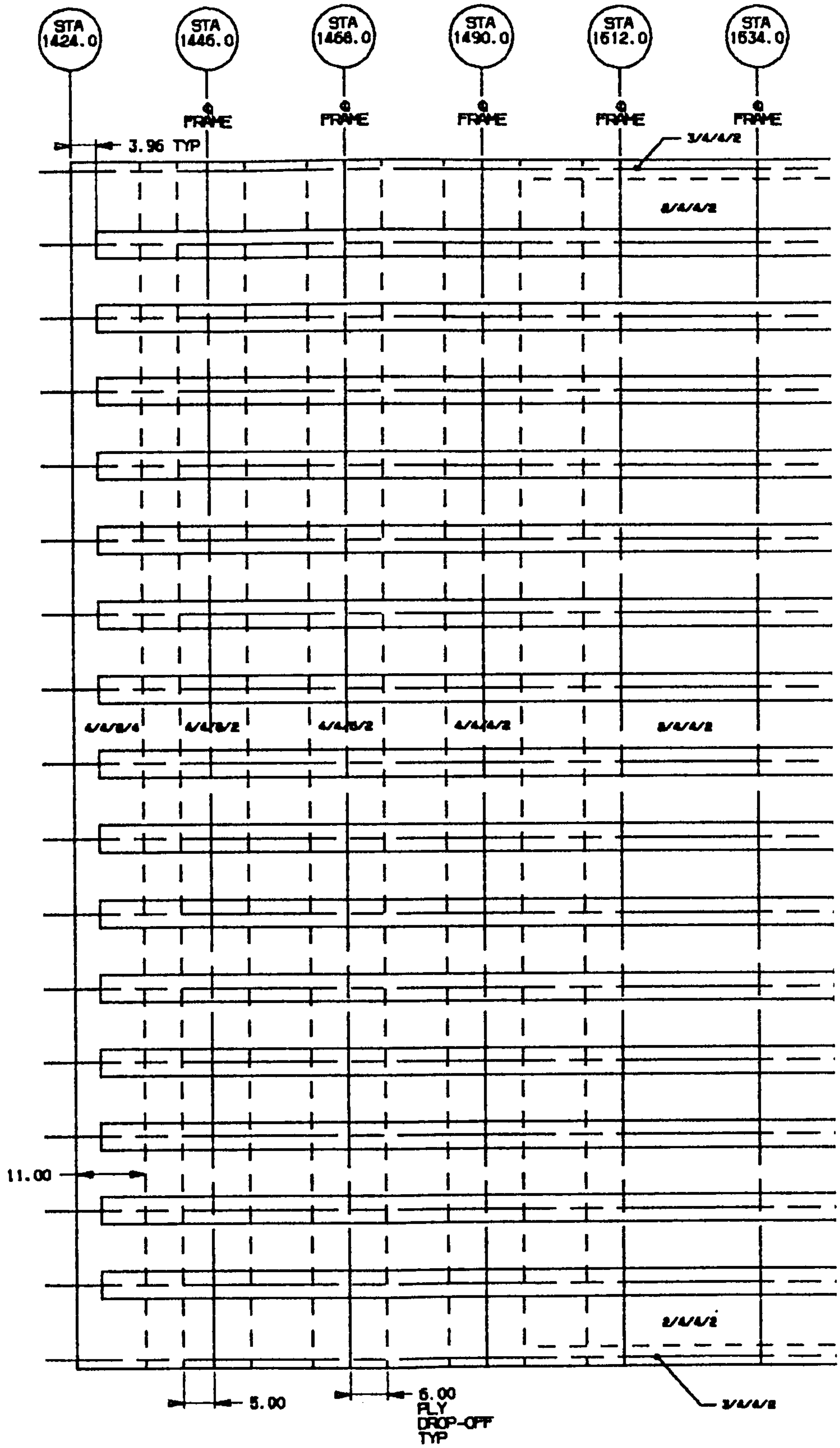
℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
℄ S-2R
℄ S-1R
℄ S-0
11.96
TYP
℄ S-1L
℄ S-2L
℄ S-3L
℄ S-4L
℄ S-5L
℄ S-6L
℄ S-7L
℄ SKIN SPLICE
R122.00(TO OML)


REAR VIEW

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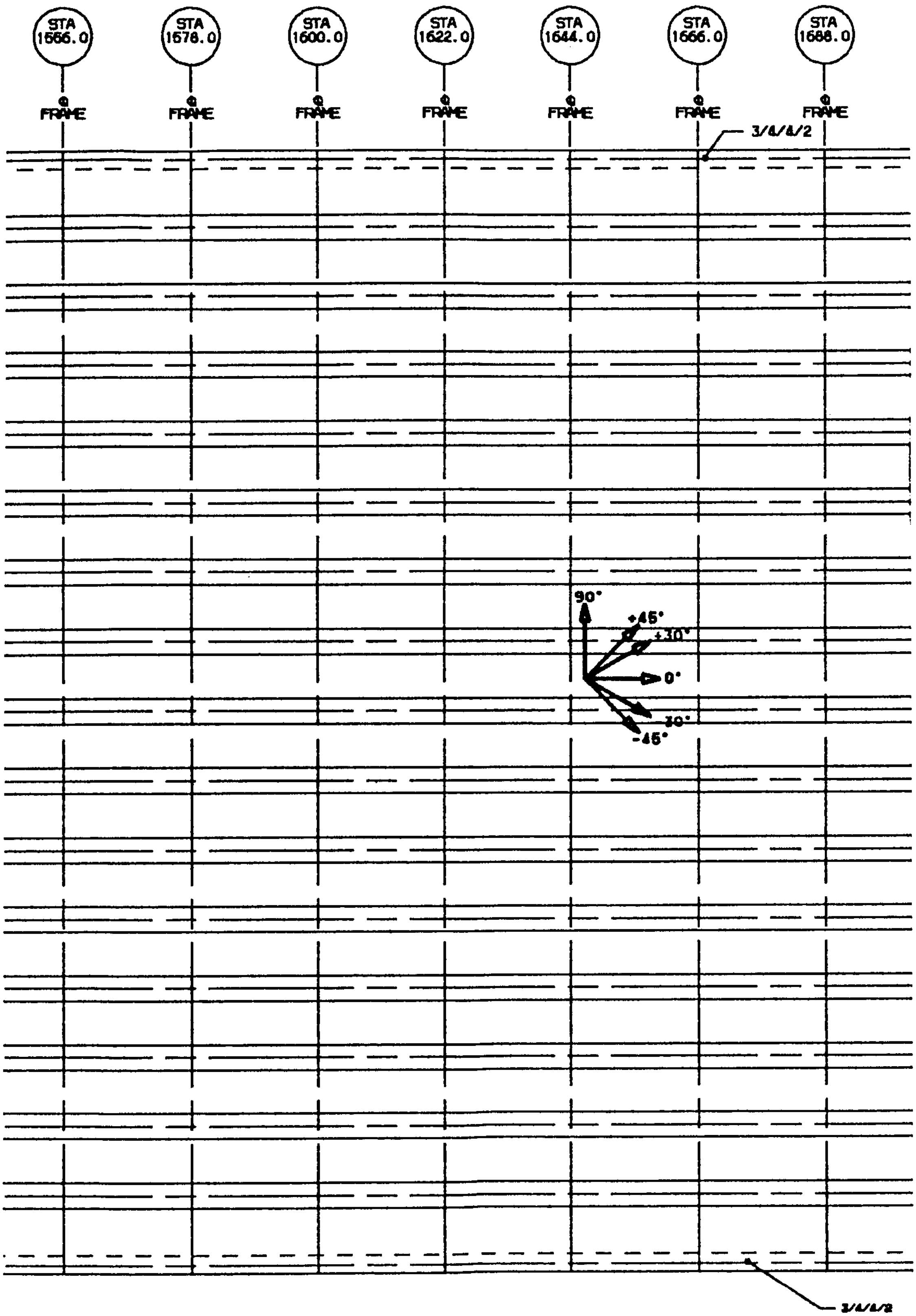
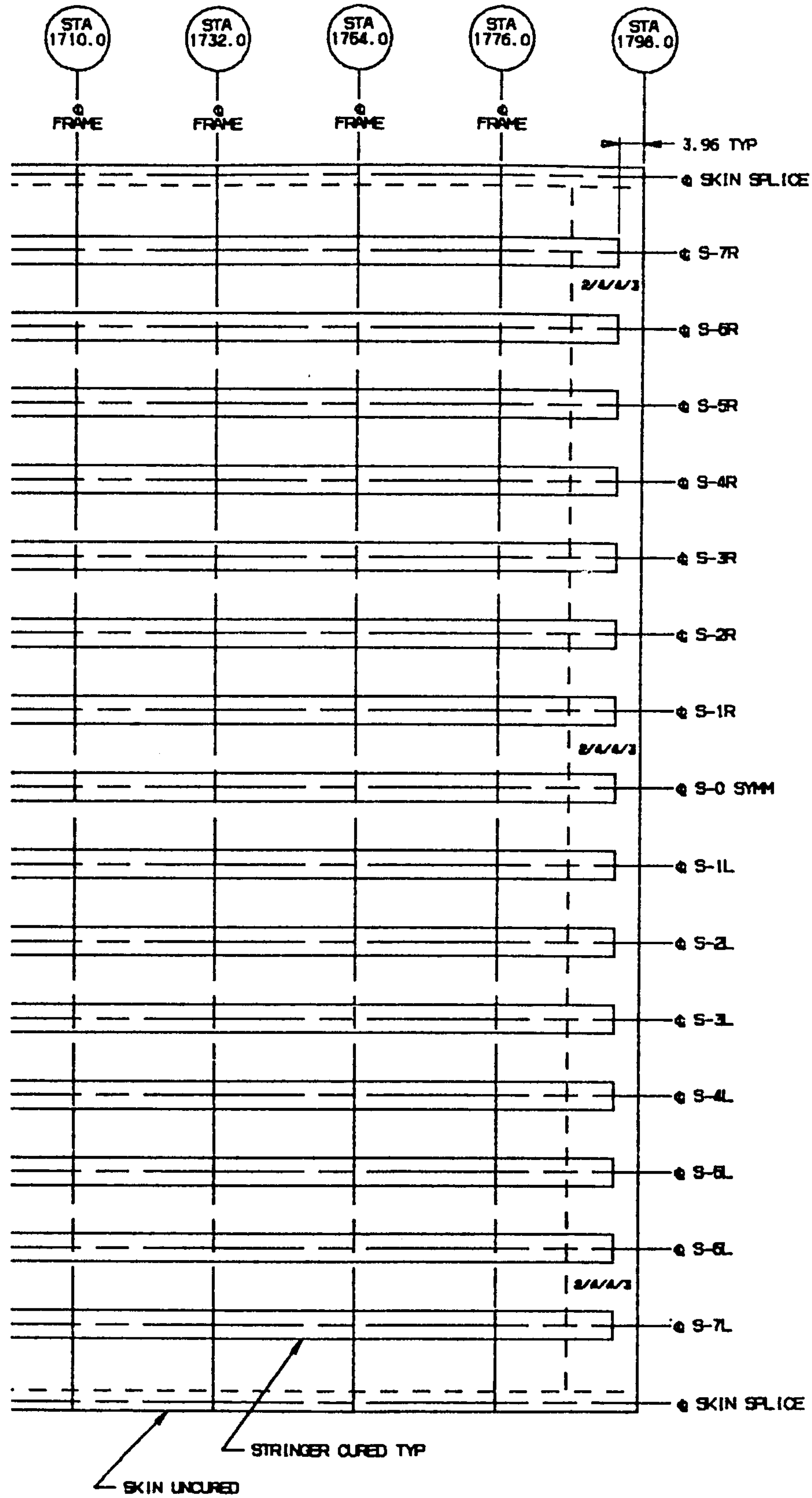



CROWN PANEL ASSY-BONDED



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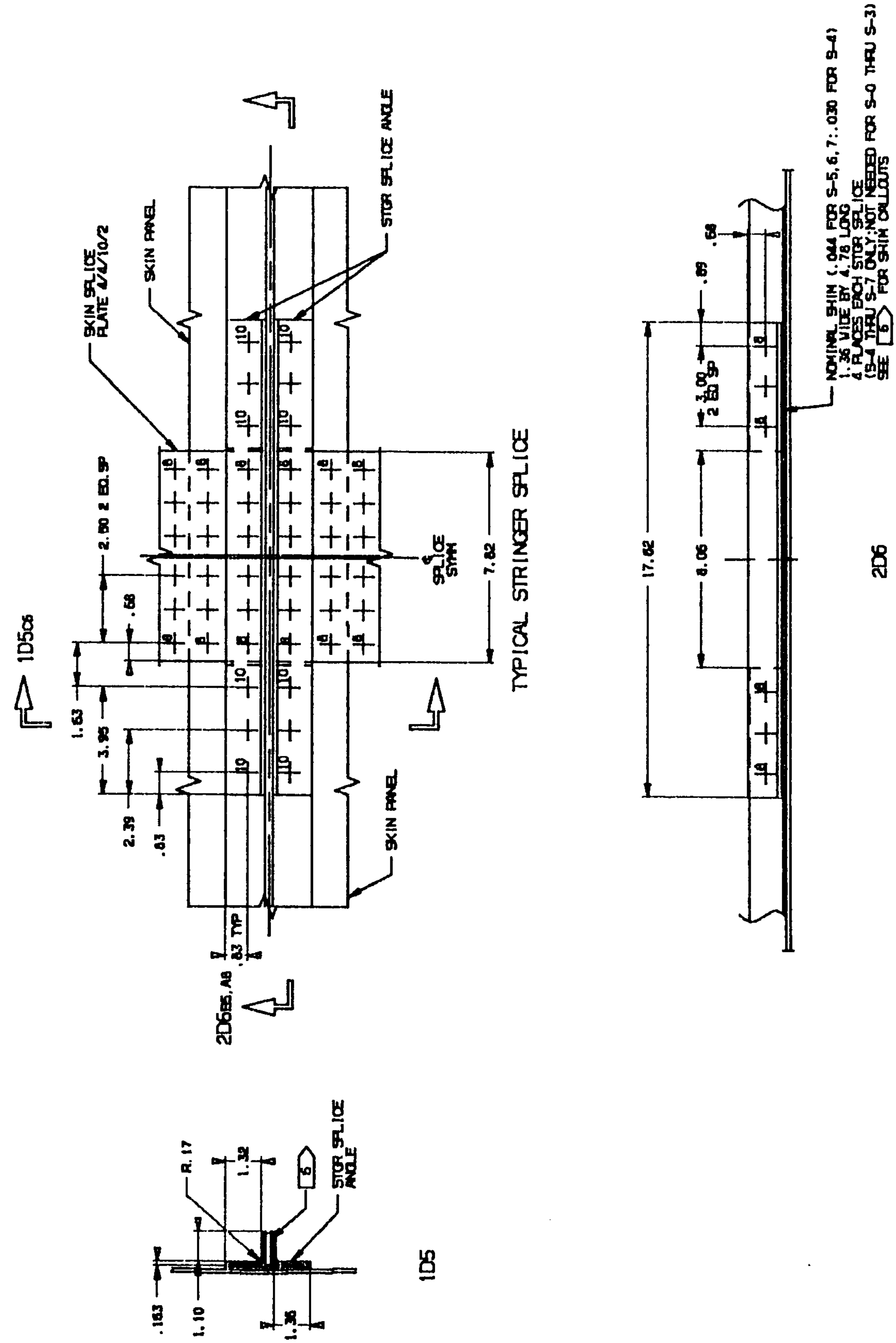
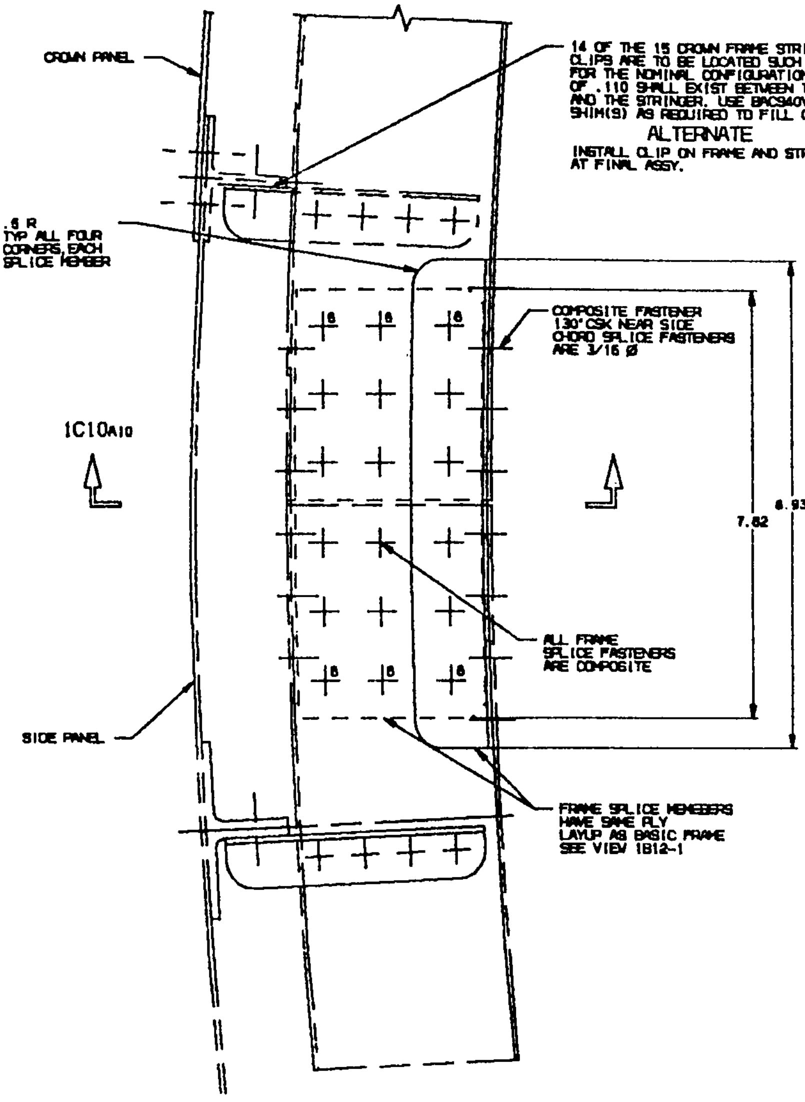
STA 1754.0
STA 1776.0
STA 1798.0
℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
3.96 TYP
℄ SKIN SPLICE
℄ S-7R
℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
℄ S-2R
℄ S-1R
℄ S-0 SYMM
℄ S-1L
℄ S-2L
℄ S-3L
℄ S-4L
℄ S-5L
℄ S-6L
℄ S-7L
℄ SKIN SPLICE
STRINGER CURED TYP
SKIN UNCURED


TYPICAL STRINGER SPLICE
SKIN SPLICE PLATE 4/4/10/2
SKIN PANEL
STGR SPLICE ANGLE
SKIN PANEL
1D5
2D6
1.63
3.95
2.39
.83
.68
2.50 2 EQ SP
7.82
.83 TYP
℄ SPLICE SYMM
R.17
1.32
1.10
.163
1.36
STGR SPLICE ANGLE
17.62
8.06
1.00 2 EQ SP
.89
.68
NOMINAL SHIM (.044 FOR S-5,6,7; .030 FOR S-4)
1.36 WIDE BY 4.78 LONG
4 PLACES EACH STGR SPLICE
(S-4 THRU S-7 ONLY; NOT NEEDED FOR S-0 THRU S-3)
SEE 5 FOR SHIM CALLOUTS

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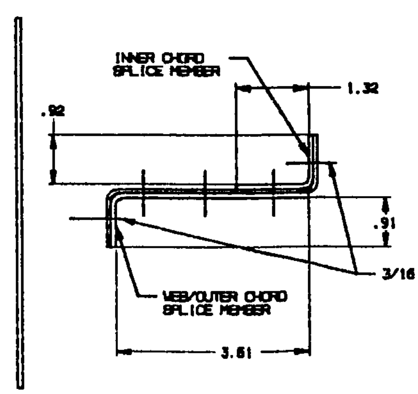
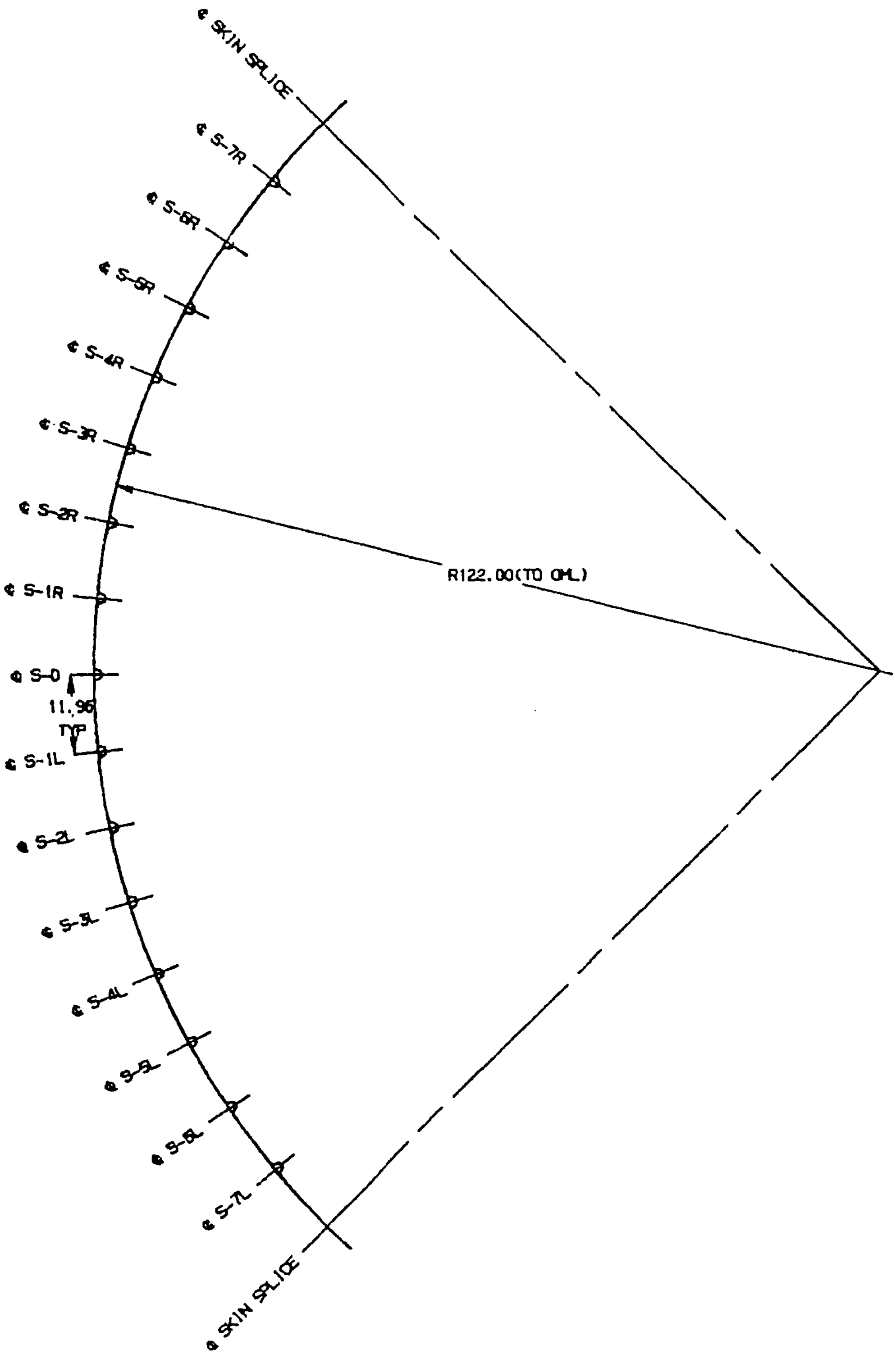



1C10

# APPENDIX C

# DESIGN C1 DEFINITION



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℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
℄ S-2R
℄ S-1R
℄ S-0
11.96
TYP
℄ S-1L
℄ S-2L
℄ S-3L
℄ S-4L
℄ S-5L
℄ S-6L
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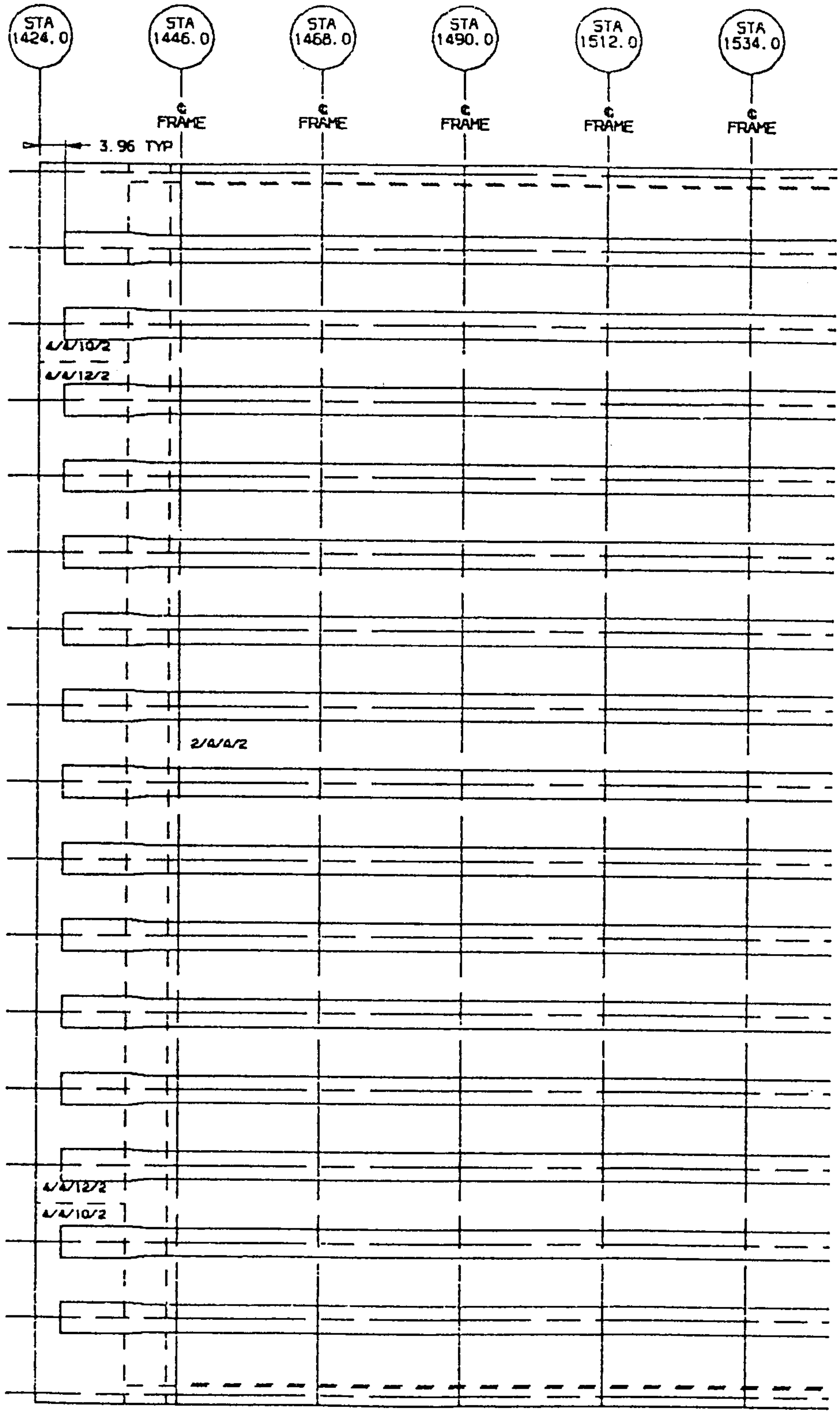
℄ SKIN SPLICE
R122.00(TO OML)


REAR VIEW

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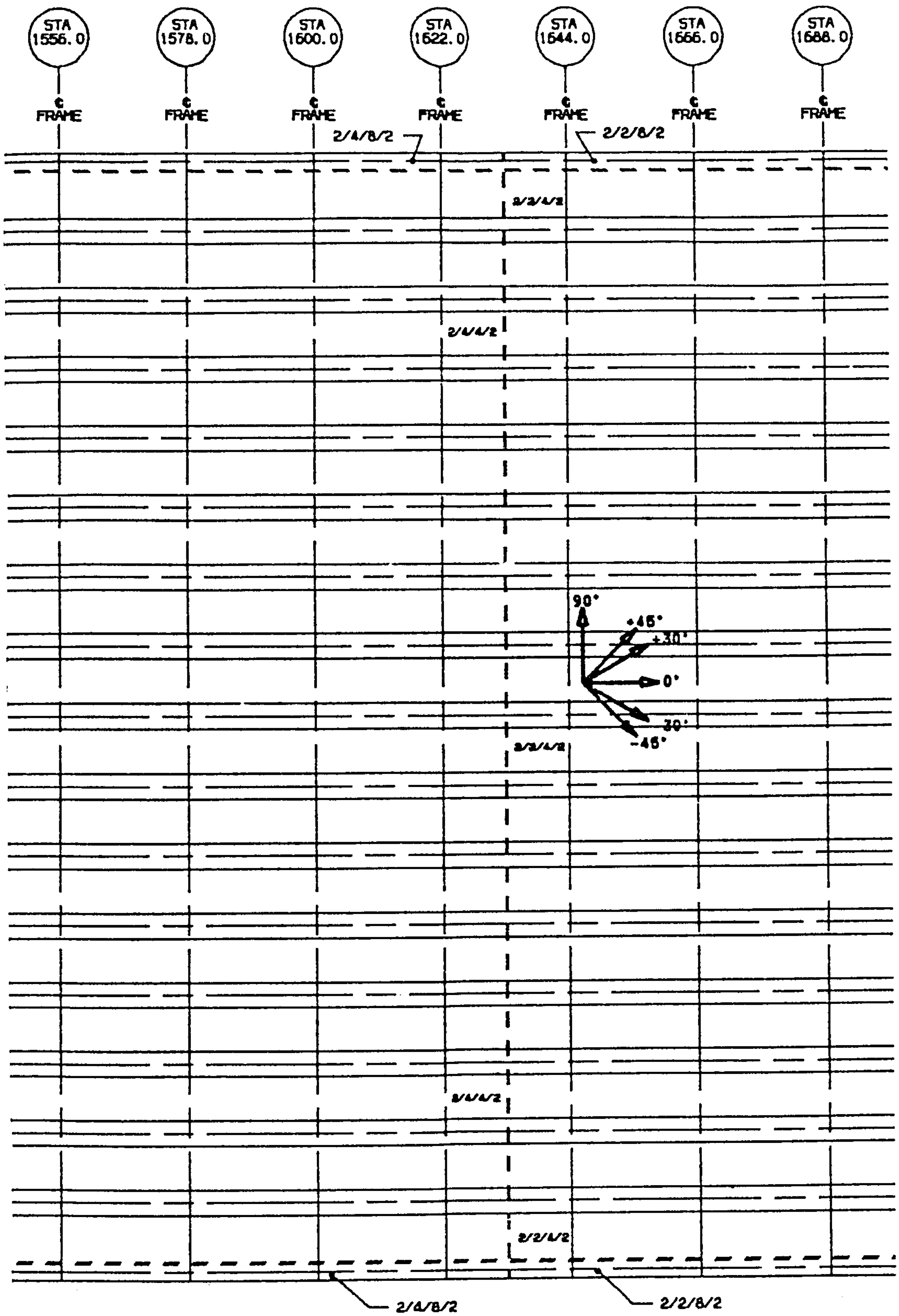
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STA 1688.0
℄ FRAME
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2/2/8/2
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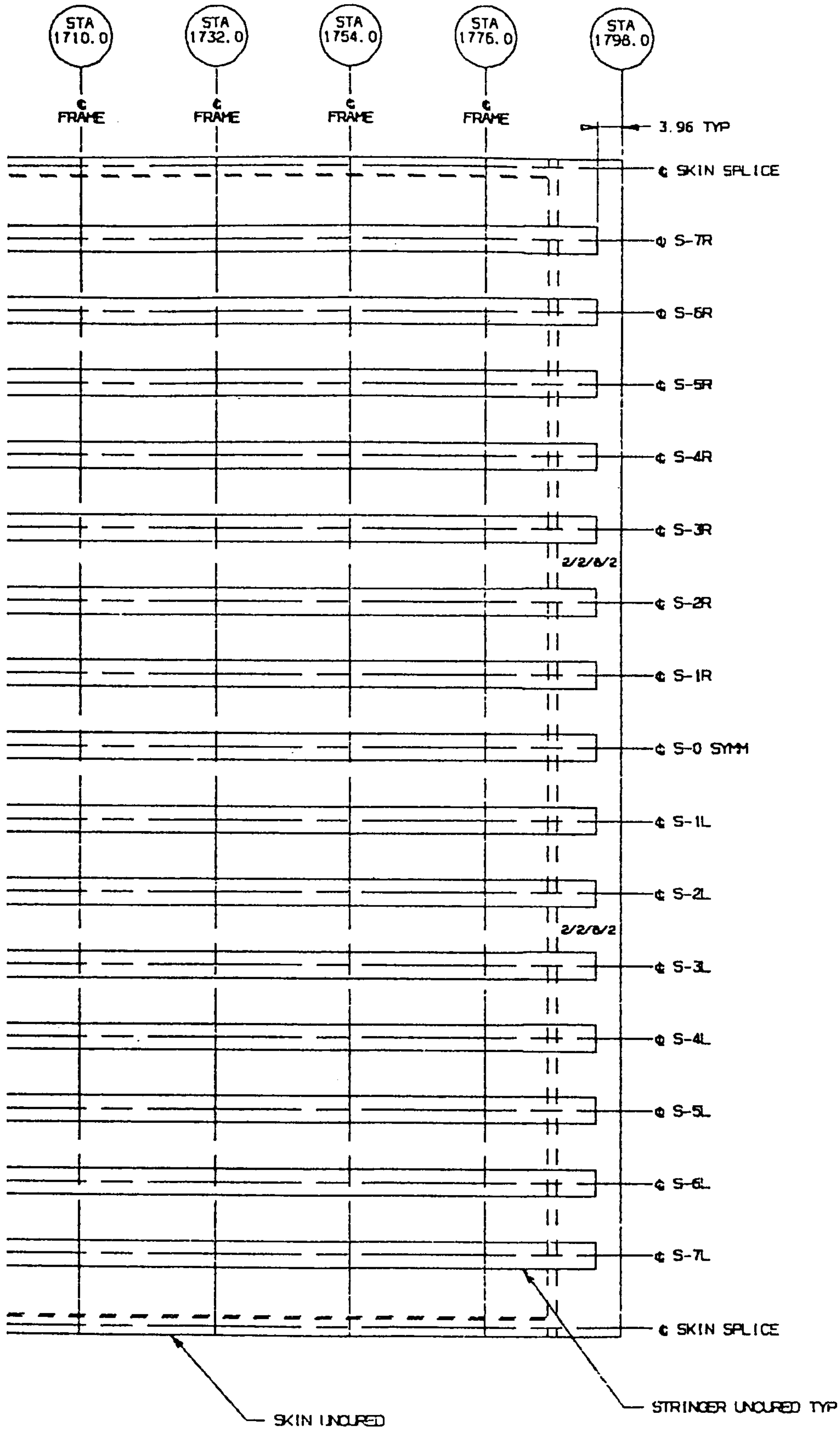
90°
+45°
+30°
0°
-30°
-45°
2/2/4/2



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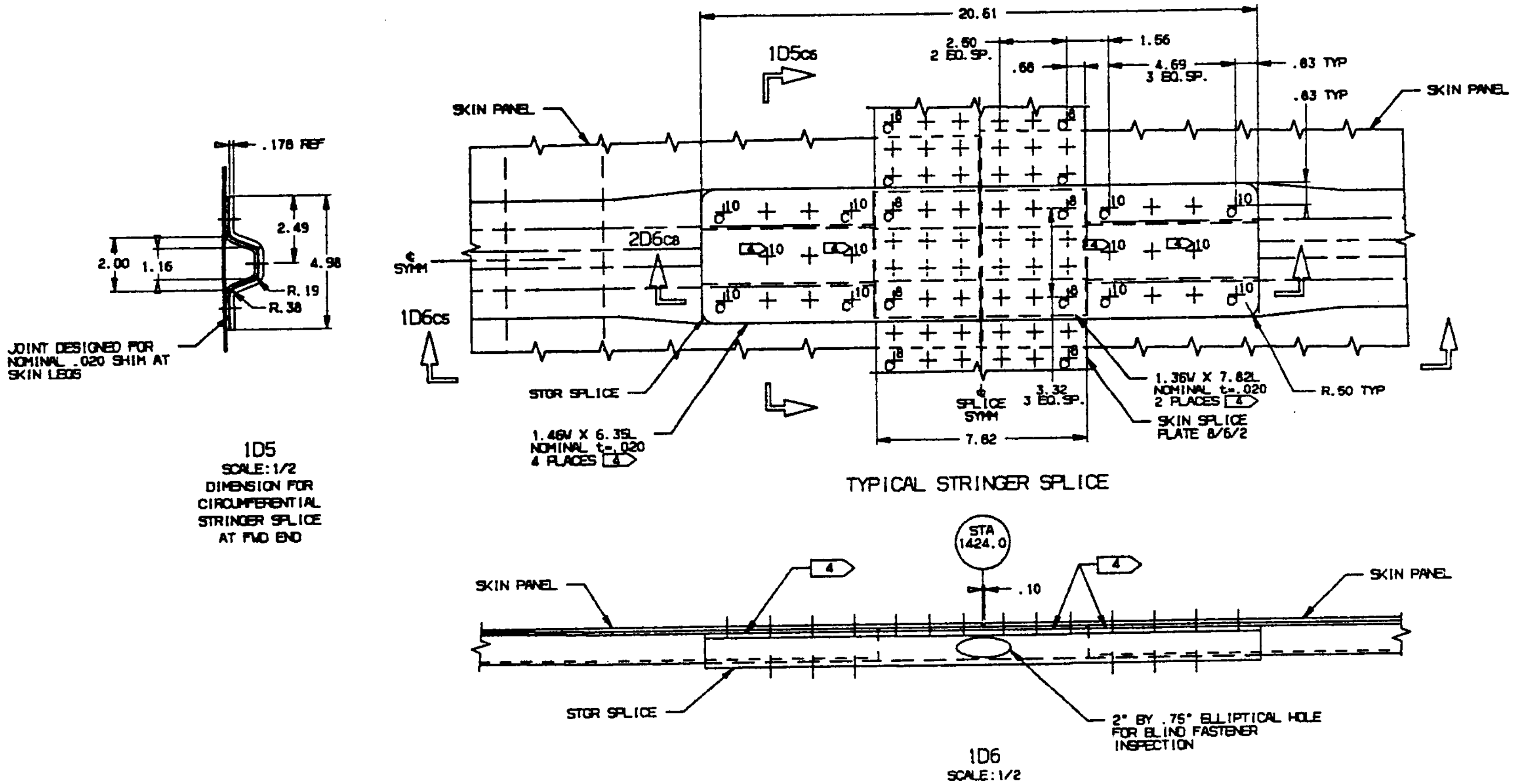
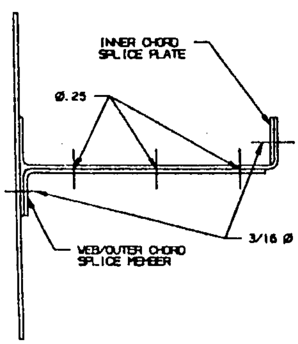
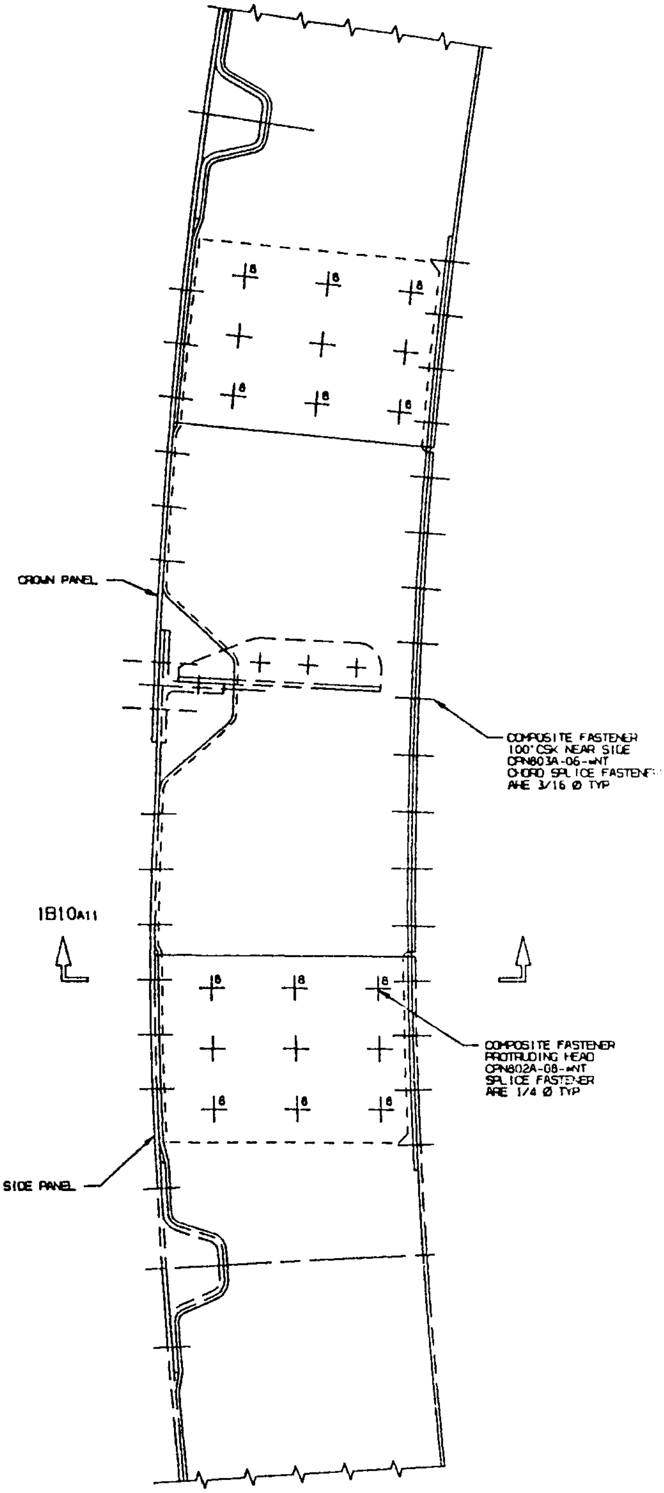
STA 1754.0
STA 1776.0
STA 1798.0
¢ FRAME
¢ FRAME
¢ FRAME
¢ FRAME
3.96 TYP
¢ SKIN SPLICE
¢ S-7R
¢ S-6R
¢ S-5R
¢ S-4R
¢ S-3R
2/2/8/2
¢ S-2R
¢ S-1R
¢ S-0 SYMM
¢ S-1L
¢ S-2L
2/2/8/2
¢ S-3L
¢ S-4L
¢ S-5L
¢ S-6L
¢ S-7L
¢ SKIN SPLICE
STRINGER UNCURED TYP
SKIN UNCURED



20.61
2.50
2 EQ. SP.
1.56
.68
4.69
3 EQ. SP.
.83 TYP
.83 TYP
1D5cs
SKIN PANEL
SKIN PANEL
.178 REF
2.49
4.98
2.00
1.16
R.19
R.38
JOINT DESIGNED FOR NOMINAL .020 SHIM AT SKIN LEGS
2D6cs
℄ SYMM
1D6cs
STGR SPLICE
1.46W X 6.35L NOMINAL t=.020 4 PLACES 4
℄ SPLICE SYMM
3.32
3 EQ. SP.
7.82
1.36W X 7.82L NOMINAL t=.020 2 PLACES 4
SKIN SPLICE PLATE 8/6/2
R.50 TYP
1D5
SCALE:1/2
DIMENSION FOR CIRCUMFERENTIAL STRINGER SPLICE AT FWD END
TYPICAL STRINGER SPLICE
STA 1424.0
.10
4
4
SKIN PANEL
SKIN PANEL
STGR SPLICE
2" BY .75" ELLIPTICAL HOLE FOR BLIND FASTENER INSPECTION
1D6
SCALE:1/2



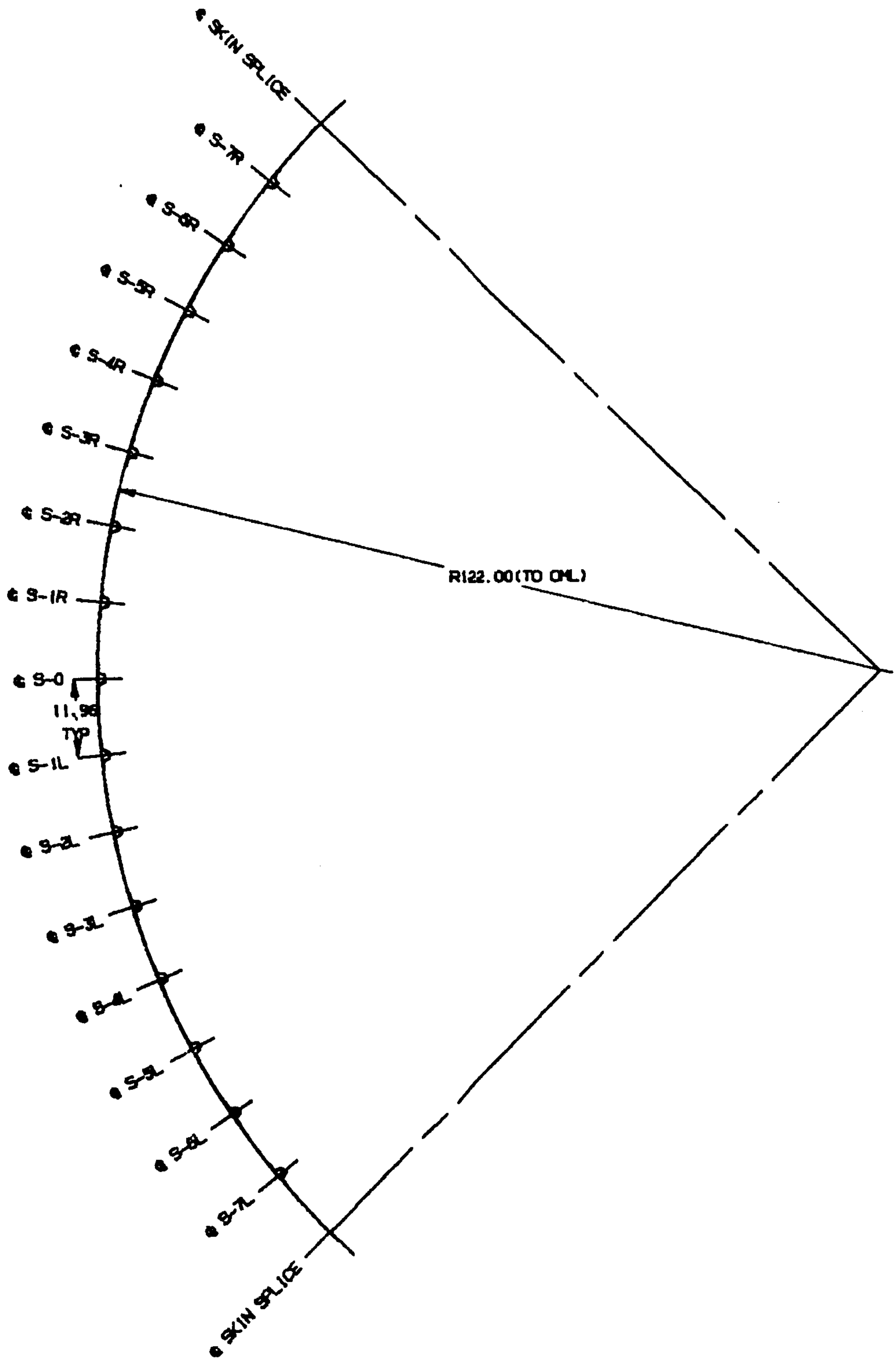

1B10
SCALE:1/1




TYPICAL FRAME SPLICE

# APPENDIX D

# DESIGN C2 DEFINITION



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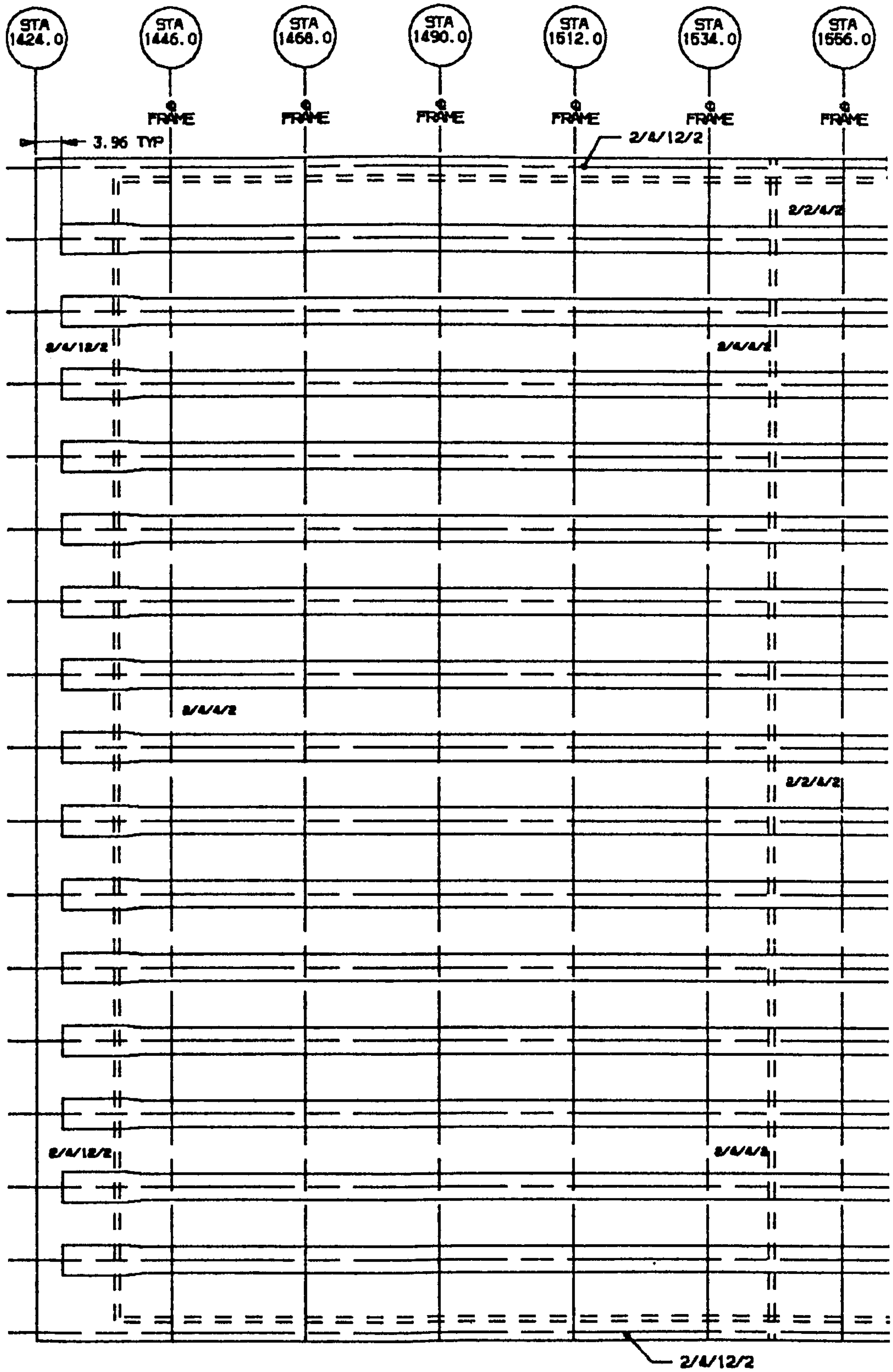
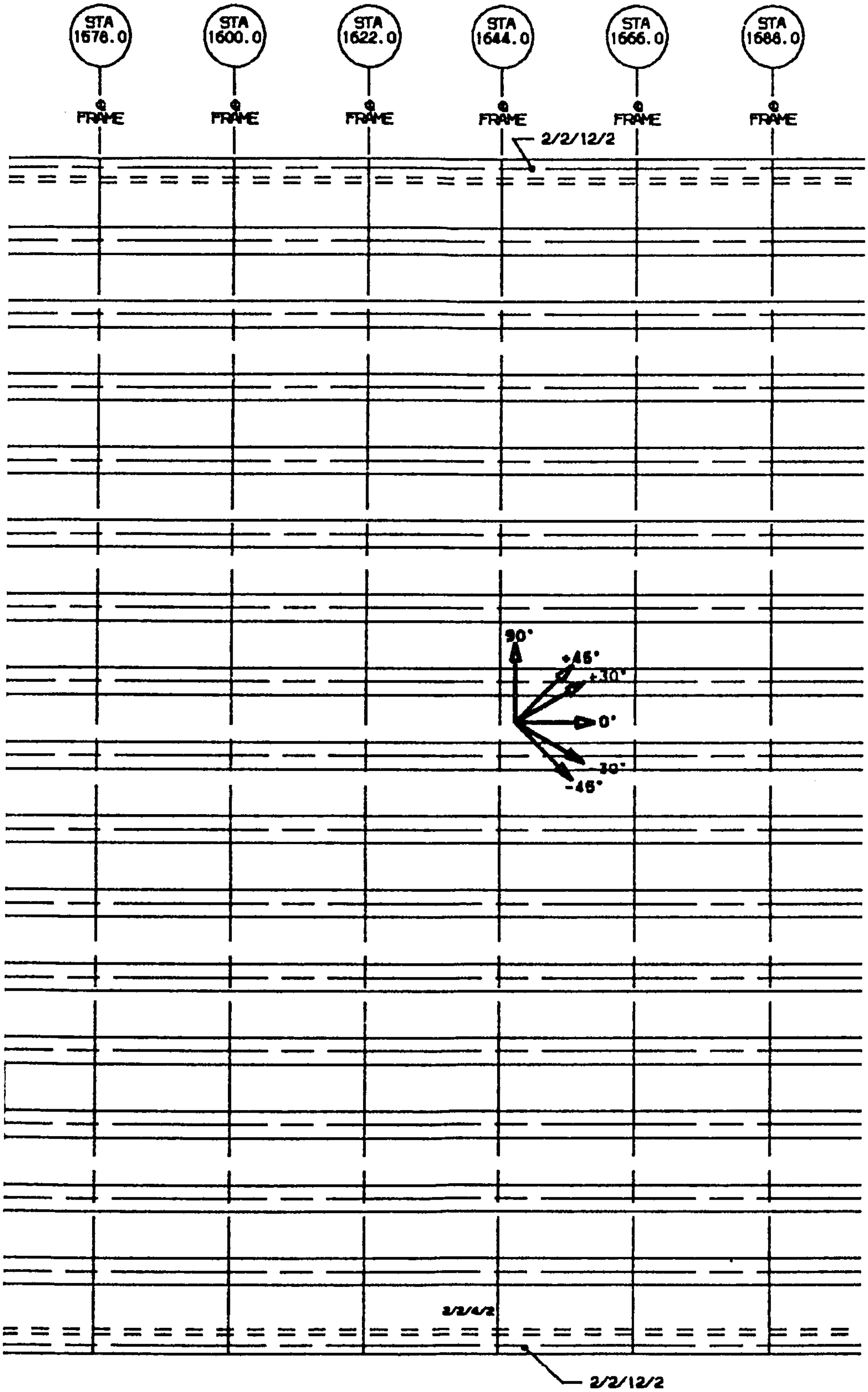
℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
℄ S-2R
℄ S-1R
℄ S-0
11.96
TYP
℄ S-1L
℄ S-2L
℄ S-3L
℄ S-4L
℄ S-5L
℄ S-6L
℄ S-7L
℄ SKIN SPLICE
R122.00(TO OML)

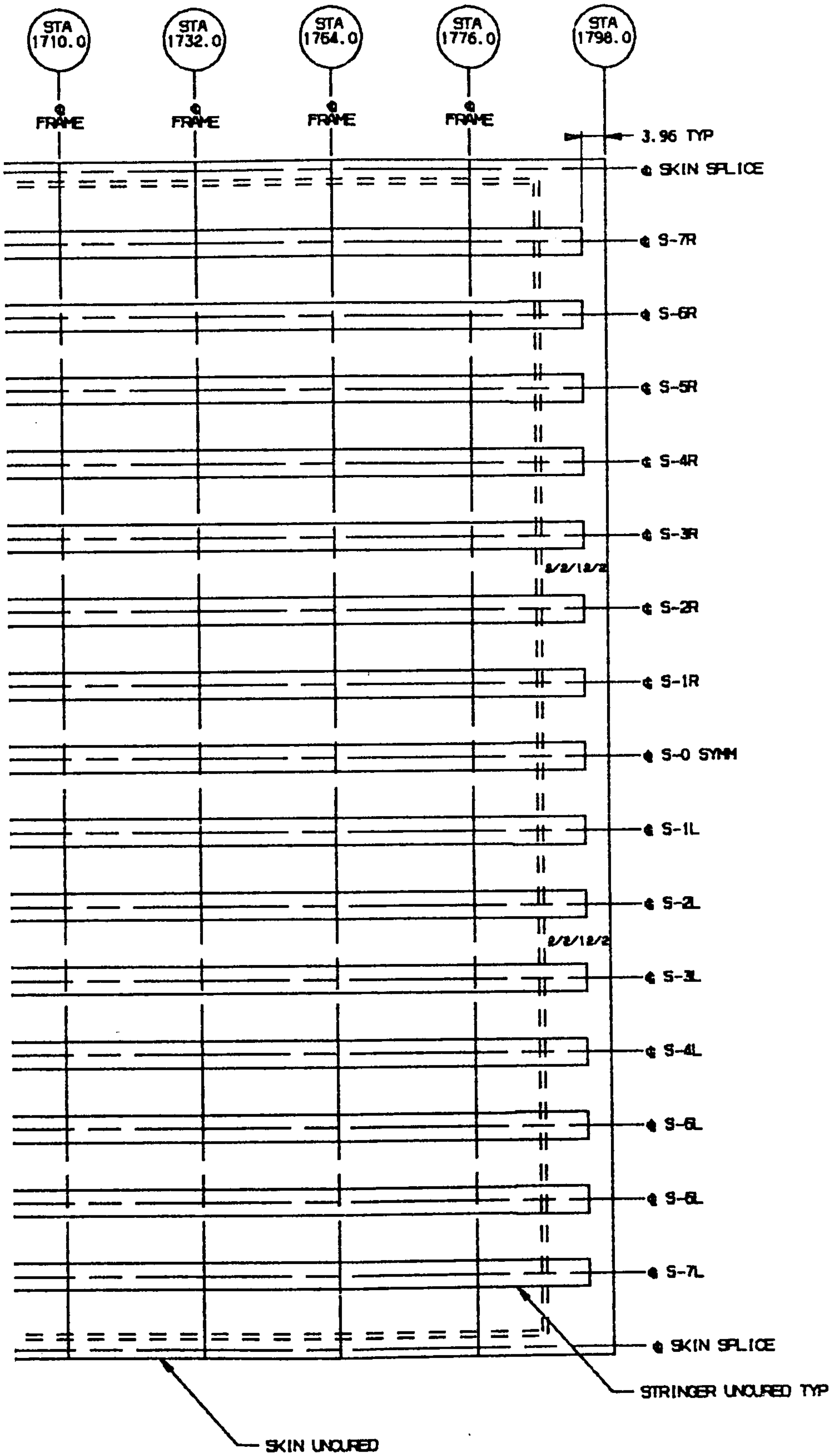

REAR VIEW




SKIN LAYUP NOTATION: QUANTITIES SHOWN ARE NUMBER OF PLIES AT PLY ANGLES (0°/±30°/±45°/90°)




CROWN PANEL ASSY-BONDED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STA 1776.0
STA 1798.0
℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
3.96 TYP
℄ SKIN SPLICE
℄ S-7R
℄ S-6R
℄ S-5R
℄ S-4R
℄ S-3R
2/2/12/2
℄ S-2R
℄ S-1R
℄ S-0 SYMM
℄ S-1L
℄ S-2L
2/2/12/2
℄ S-3L
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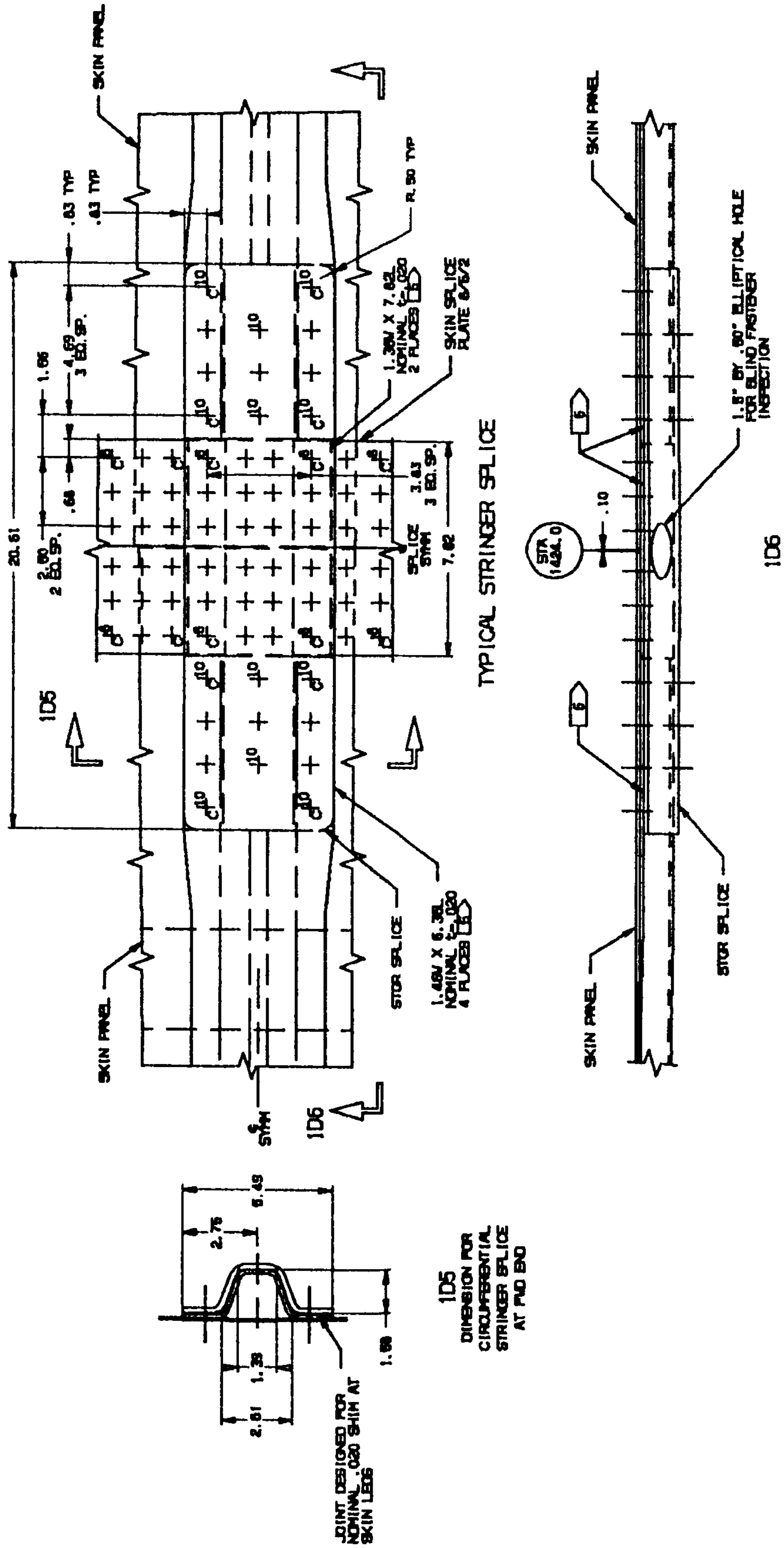
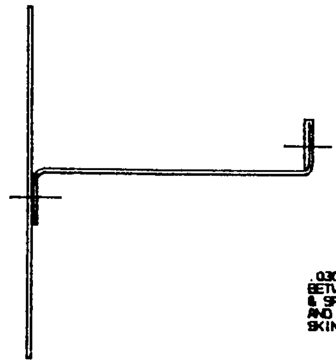
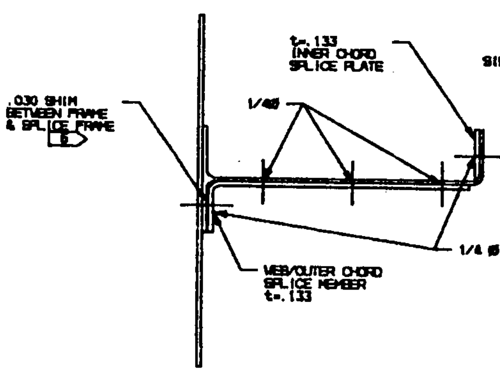
℄ SKIN SPLICE
STRINGER UNCURED TYP
SKIN UNCURED

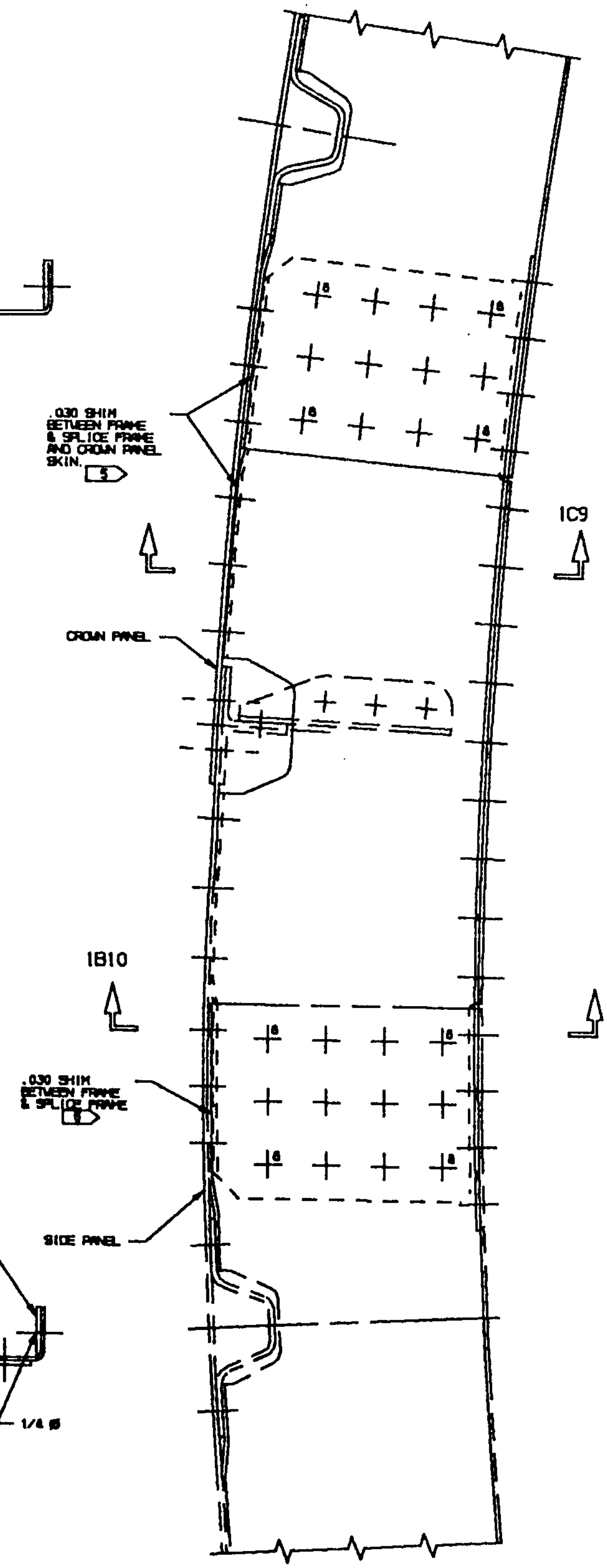

TYPICAL STRINGER SPLICE
SKIN PANEL
SKIN SPLICE PLATE 8/6/2
STGR SPLICE
SPLICE SYMM
1D5
1D6
1.8" BY .60" ELLIPTICAL HOLE FOR BLIND FASTENER INSPECTION
DIMENSION FOR CIRCUMFERENTIAL STRINGER SPLICE AT FWD END
JOINT DESIGNED FOR NOMINAL .020 SHIM AT SKIN LEGS



1C9



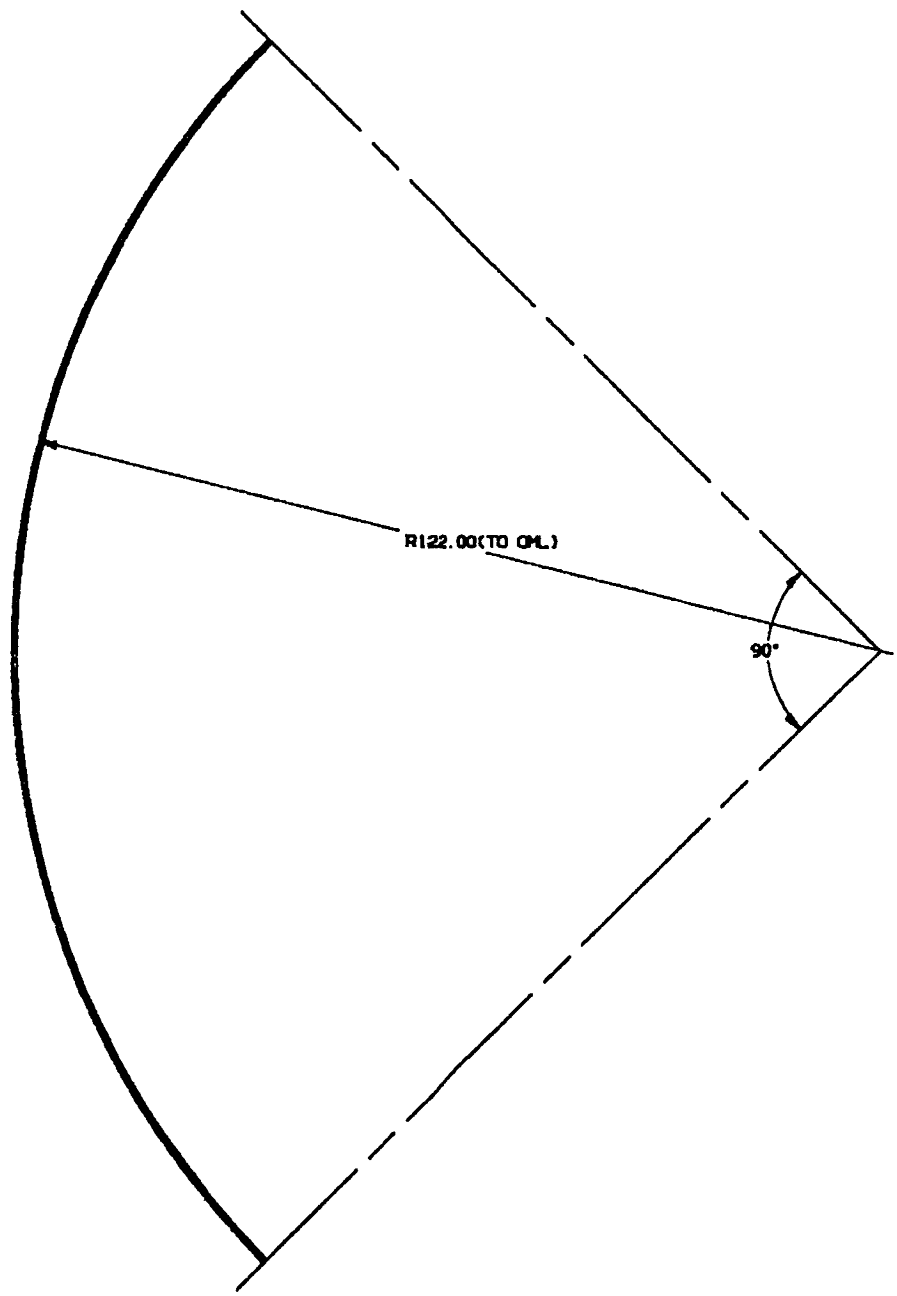

1B10



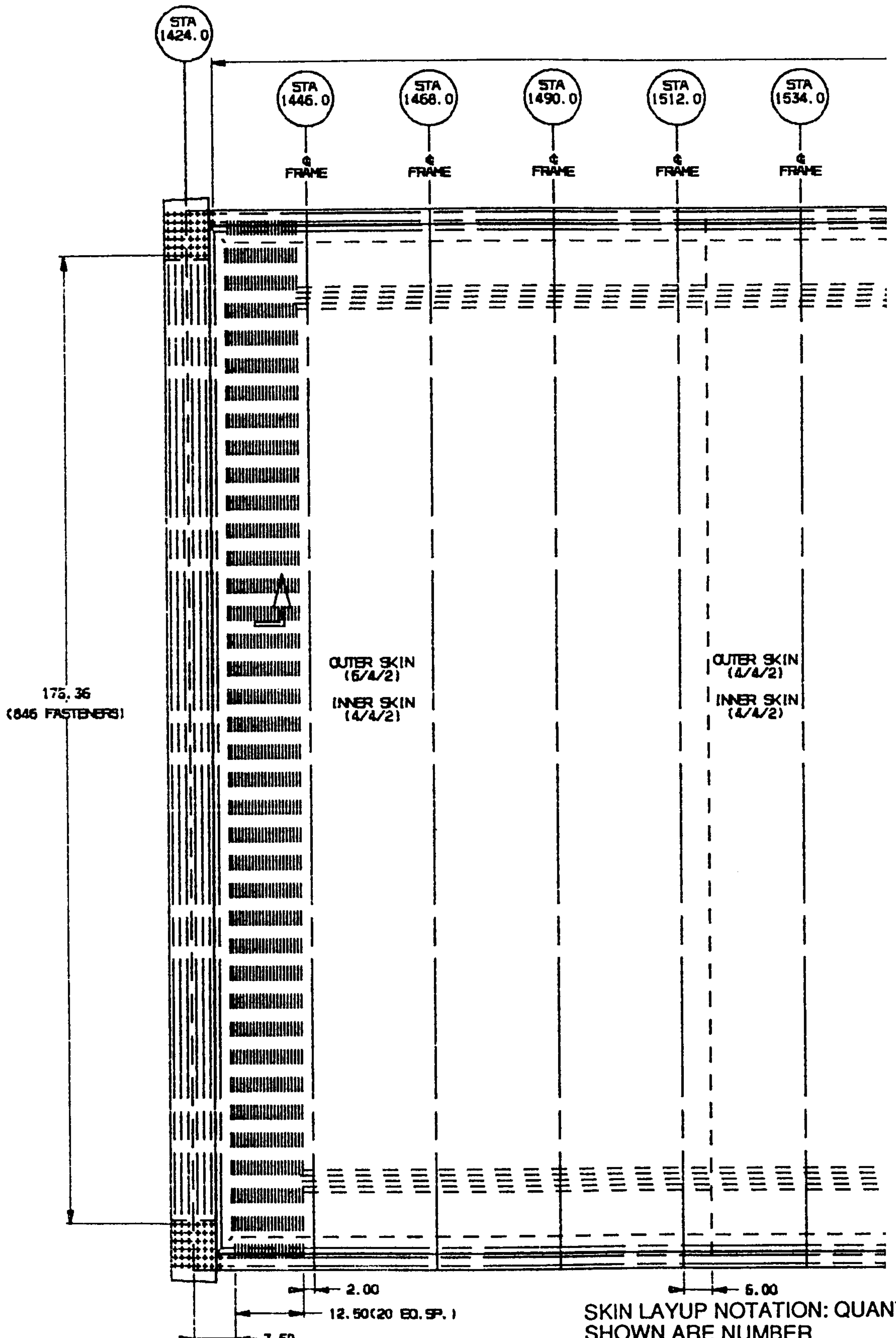

TYPICAL FRAME SPLICE

# APPENDIX E

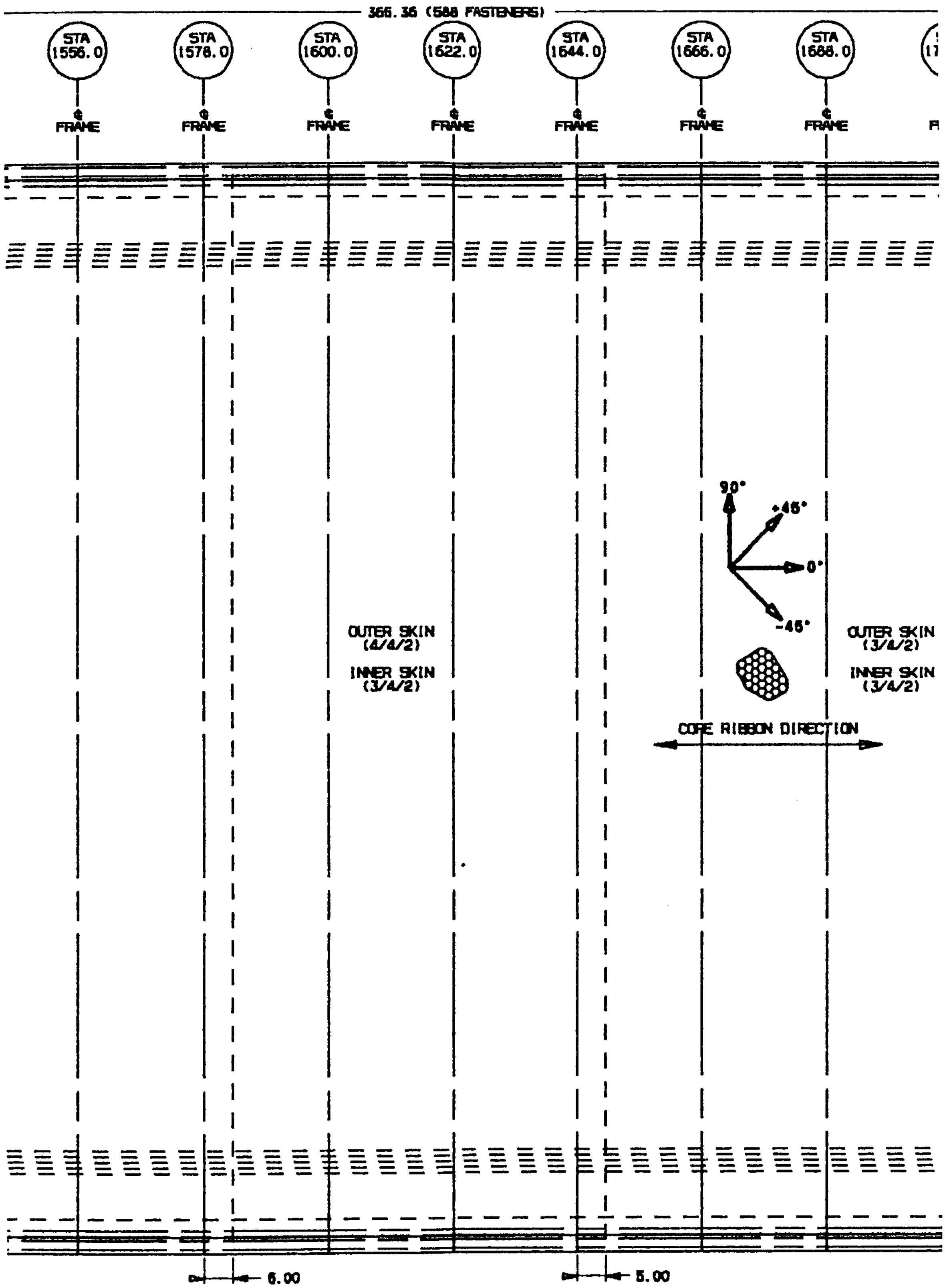
# DESIGN D1 DEFINITION



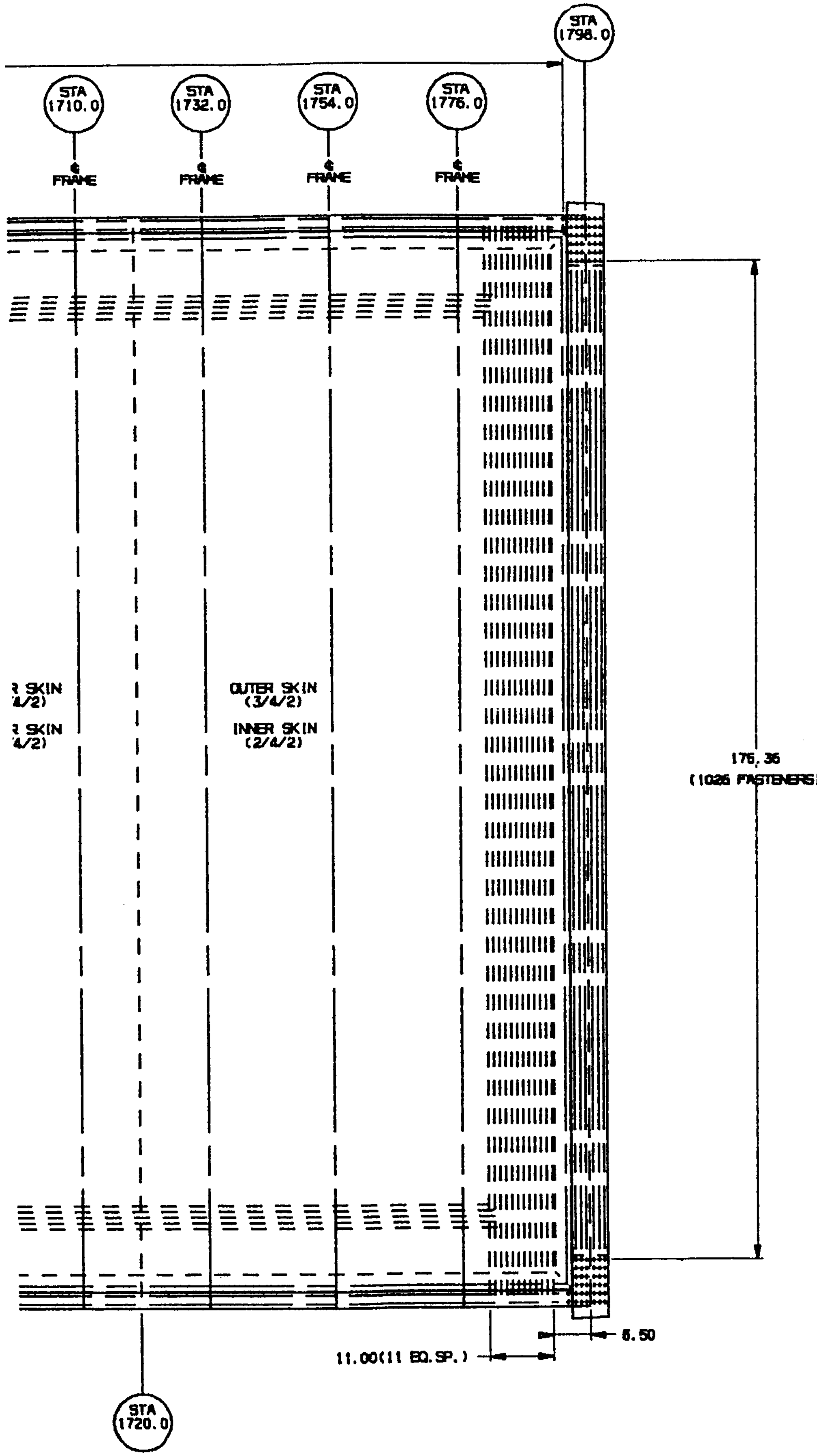

REAR VIEW

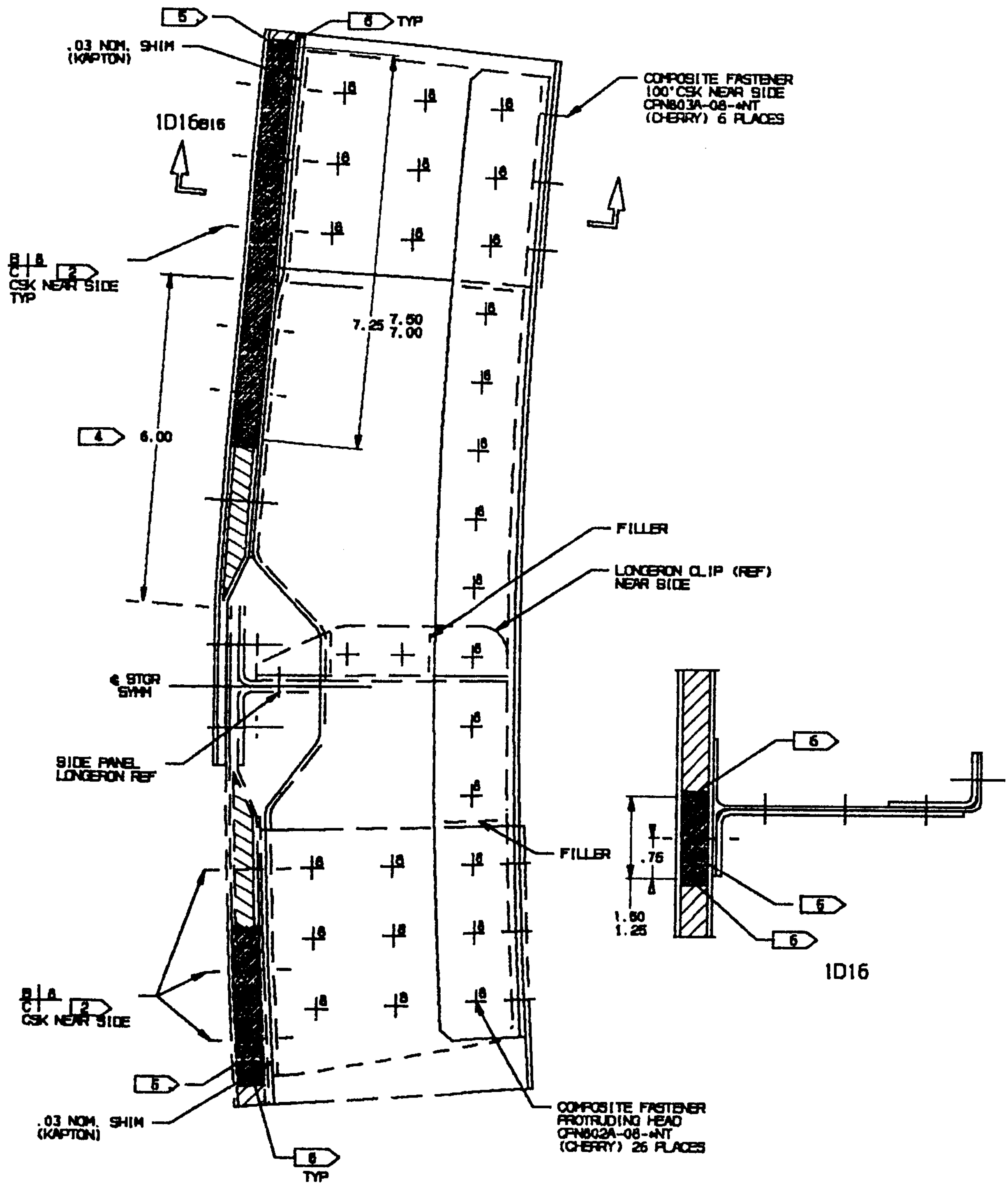



SKIN LAYUP NOTATION: QUANTITIES SHOWN ARE NUMBER OF PLIES AT PLY ANGLES (0°/±45°/90°)




CROWN PANEL ASSY-BONDED

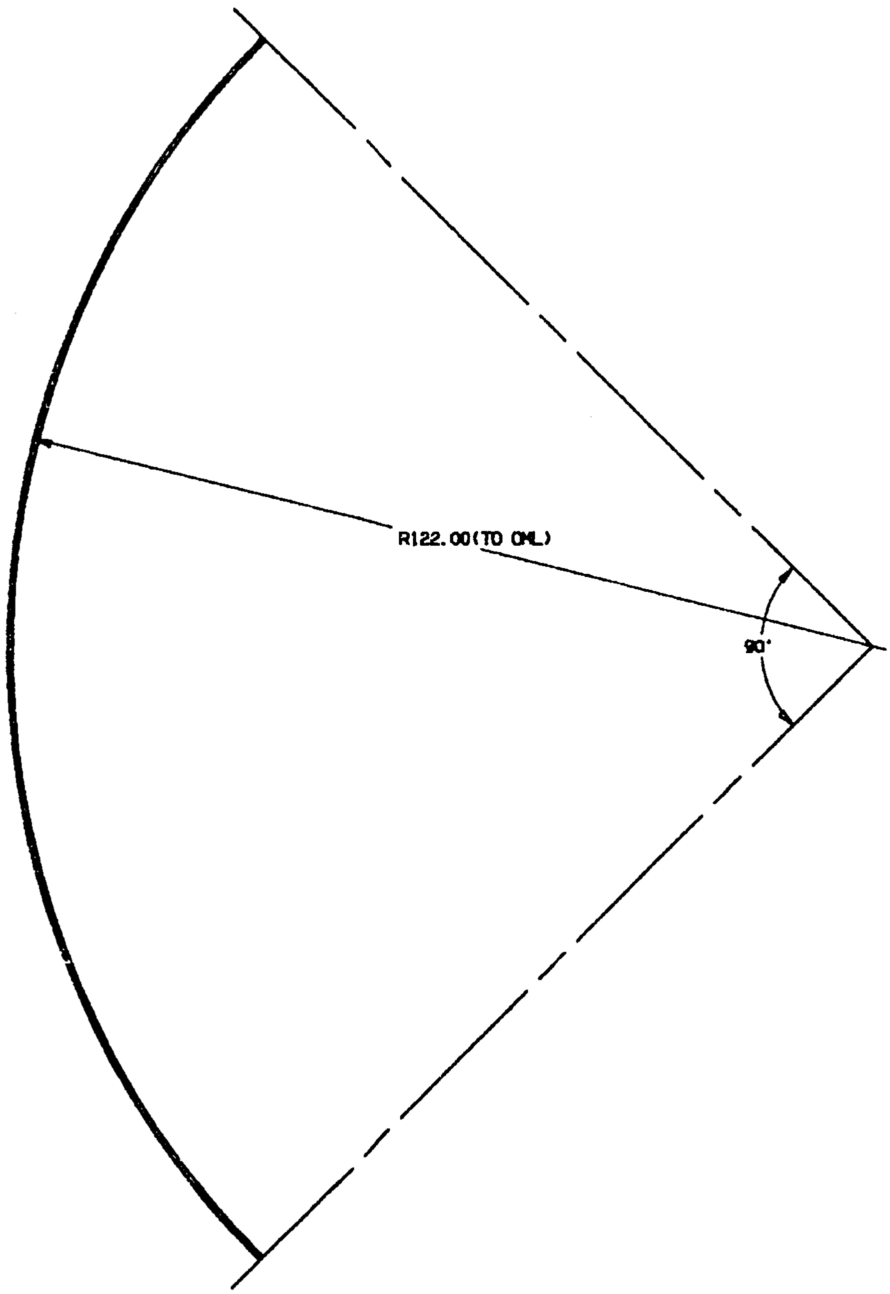

STA 1798.0
STA 1710.0
STA 1732.0
STA 1754.0
STA 1776.0
℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
R SKIN
/4/2)
R SKIN
/4/2)
OUTER SKIN
(3/4/2)
INNER SKIN
(2/4/2)
176.36
(1026 FASTENERS)
6.50
11.00(11 EQ.SP.)
STA 1720.0



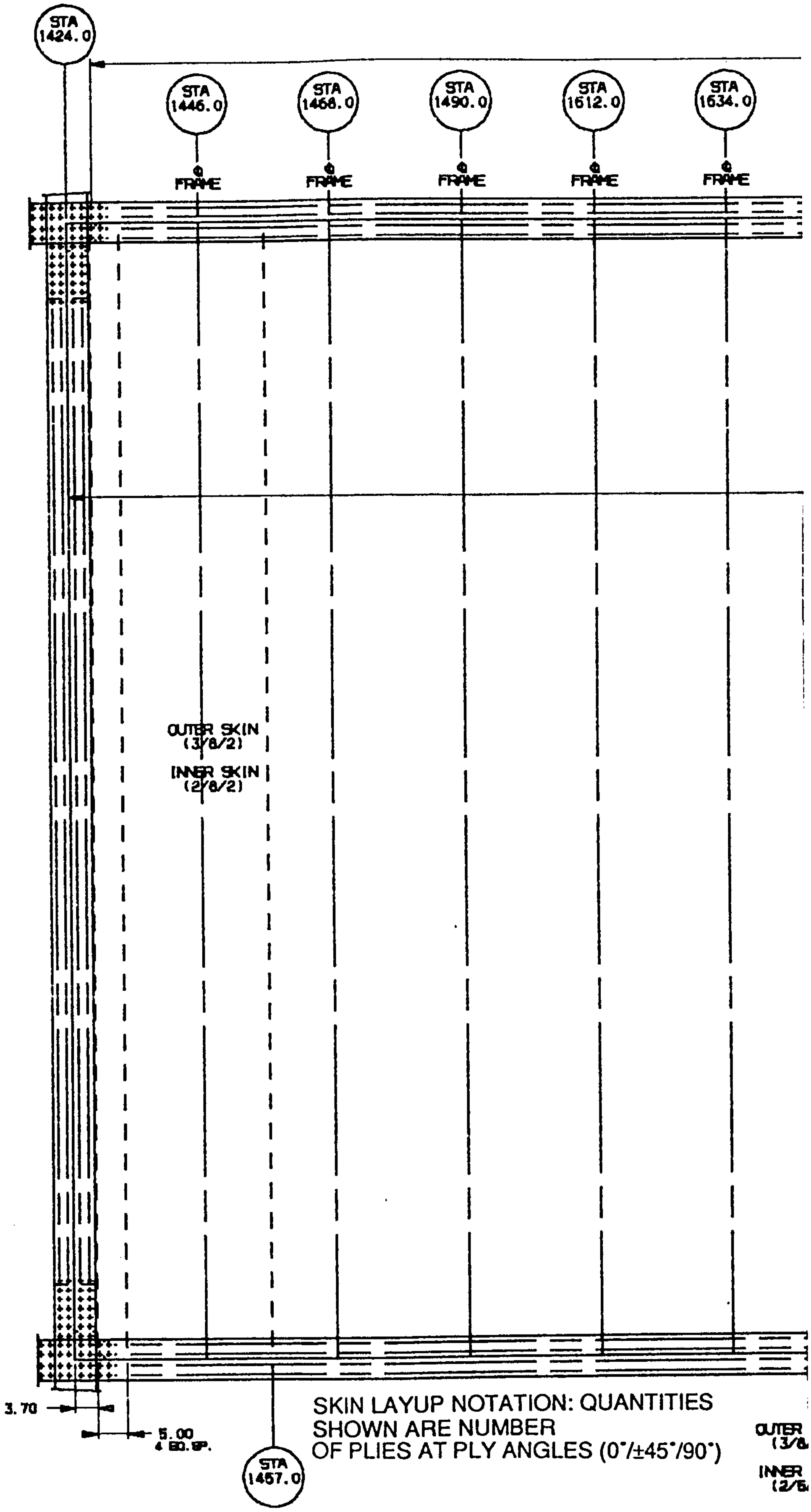

TYPICAL FRAME SPLICE

# APPENDIX F

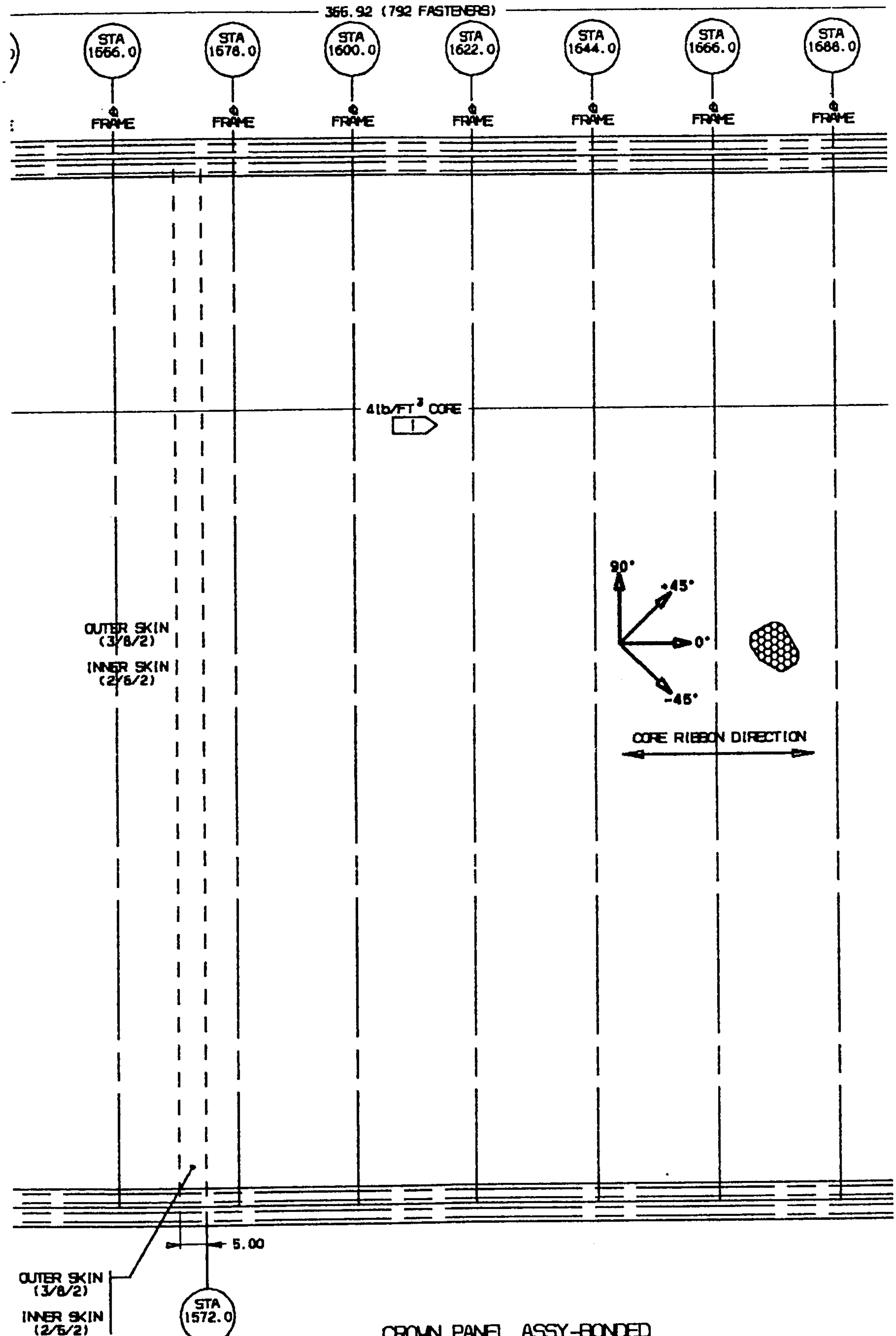
# DESIGN D2 DEFINITION



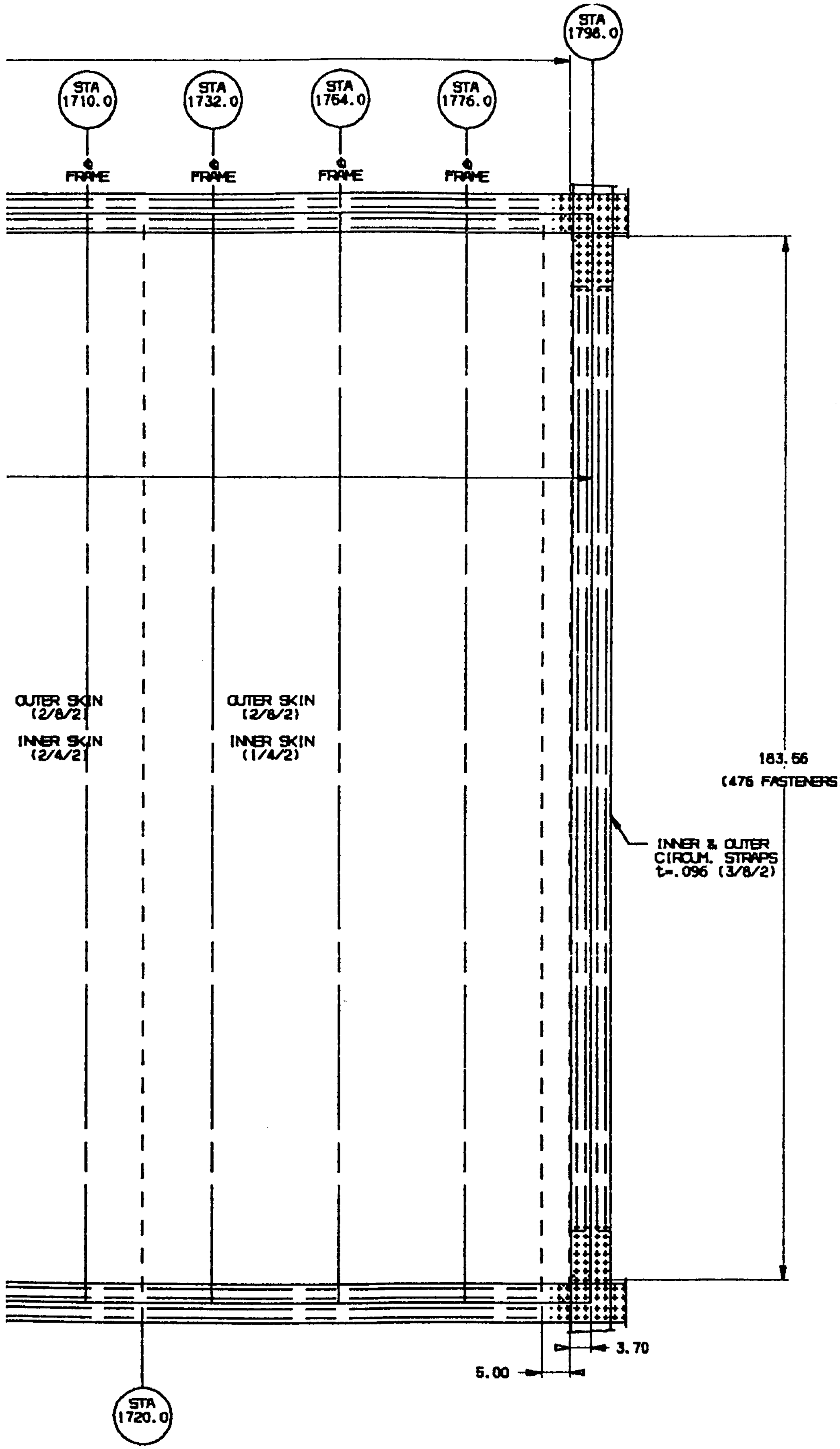

REAR VIEW



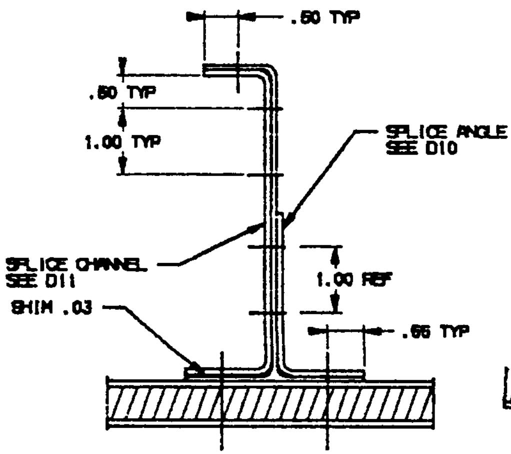

SKIN LAYUP NOTATION: QUANTITIES SHOWN ARE NUMBER OF PLIES AT PLY ANGLES (0°/±45°/90°)



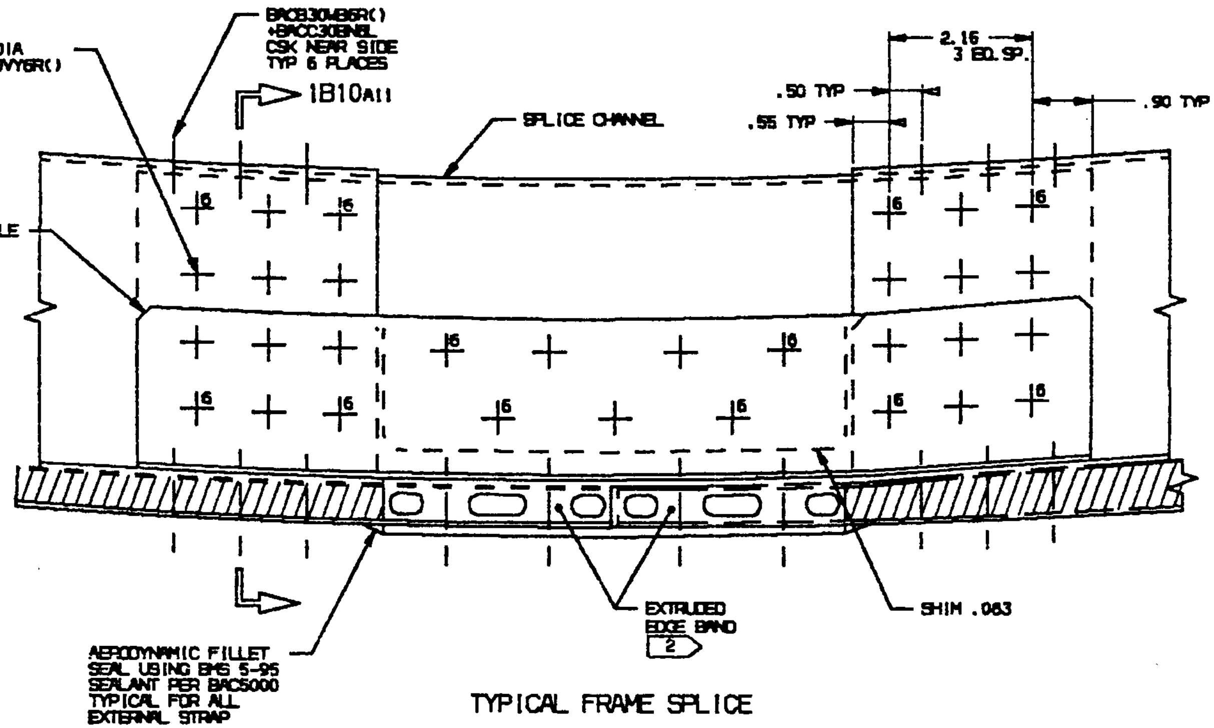

CROWN PANEL ASSY-BONDED
1D2



STA 1798.0
STA 1710.0
STA 1732.0
STA 1754.0
STA 1776.0
℄ FRAME
℄ FRAME
℄ FRAME
℄ FRAME
OUTER SKIN (2/8/2)
INNER SKIN (2/4/2)
OUTER SKIN (2/8/2)
INNER SKIN (1/4/2)
183.56
(476 FASTENERS)
INNER & OUTER CIRCUM. STRAPS t=.096 (3/8/2)
3.70
5.00
STA 1720.0




1B10




TYPICAL FRAME SPLICE

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L. B. Ilcewicz, T. H. Walker, K. S. Willden, G. D. Swanson, G. Truslove, S. L. Metschan, and C. L. Pfahl

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Relationships between manufacturing costs and design details must be understood to promote the application of advanced composite technologies to transport fuselage structures. A team approach, integrating the disciplines responsible for aircraft structural design and manufacturing, was developed to perform cost and weight trade studies for a twenty-foot diameter aft fuselage section. Baseline composite design and manufacturing concepts were selected for large quadrant panels in crown, side, and keel areas of the fuselage section. The associated technical issues were also identified. Detailed evaluation of crown panels indicated the potential for large weight savings and costs competitive with aluminum technology in the 1995 timeframe. Different processes and material forms were selected for the various elements that comprise the fuselage structure. Additional cost and weight savings potential was estimated for future advancements.

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