# Air Superiority Fighter Wing Structure Design For Improved Cost, Weight, and Integrity

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**This program was one of several programs sponsored by the Air Force Flight Dynamics Lab to investigate new structural designs, which would be lighter, lower in cost, and have improved reliability, when compared to a given baseline. The structure investigated in this program was that of a fighter wing, and the baseline chosen was the wing and carrythrough structure of the Northrop F-5E Air Superiority Fighter. The approach was to integrate systematically innovative design concepts, new materials, and advanced manufacturing methods. A further requirement was that the new designs had to meet the latest Air Force damage tolerance requirements. An integral part of the program was a comprehensive materials test program. A variety of configurations studied included features and combinations, such as: full-depth honeycomb, integally stiffened, thick-skin, and sandwich panel covers; various arrangements and constructions of spars; mechanically attached, welded, and adhesive bonded assemblies; and aluminum and titanium alloys. Weight and cost comparisons were obtained. From the studies, design concepts were evolved for further study.**

## Introduction

RECENT structural difficulties in Air Force Weapon Systems have focused attention on problems which heretofore concerned only the structure and materials specialists. These difficulties served to emphasize the need for a long-term Advanced Development Program (ADP) concerned with improvements in metallic aircraft structures. Major hardware programs, which integrate and exploit new design concepts, fracture mechanics, analysis methods, design criteria, materials, manufacturing methods, nondestructive inspection, and information transfer methods were required as part of this ADP to anticipate and solve critical aircraft structural problems prior to the acquisition of new Air Force Weapon Systems.

## Overall Program Goal

The overall goal of the ADP was to reduce the risk of structural failure of future Air Force aircraft by increasing their structural reliability, integrity, and efficiency. This goal was to be achieved through the integration, exploitation, application, and demonstration of new or improved structures, materials, and manufacturing technologies. Development and application of fracture mechanics techniques were integral to this program. The increased structural reliability, integrity, and efficiency of the assemblies built and tested under this ADP was to result in a similar payoff to the Air Force by a thorough, timely information transfer to future systems of the demonstrated improvements in the structures, materials, and manufacturing technology base.

## Objective

The objective of this preliminary design study was to evolve, evaluate, and compare new structural concepts to reduce the weight of a fighter wing and carrythrough structure while maintaining its cost and life approximately equivalent to a representative advanced lightweight fighter system. To achieve this objective, advantage was to be taken of a) innovative design concepts and applications; and b) new and improved materials, processes, and manufacturing methods which generally have had sufficient development to show near-term potential for possible application to next generation systems—operational in about the latter 1970's or early 1980's. It was also necessary that all of the advanced structural design concepts comply with the damage tolerance requirements of MIL-A-008866, Revision D, dated Aug. 1972.

## Baseline

To provide a realistic set of requirements and parameters upon which to focus the studies conducted under this program, it was necessary to select a suitable baseline airplane and wing component. These requirements and parameters were to set such factors as: 1) general geometry and size of the wing; 2) loading intensities (static and fatigue); 3) operational performance boundaries (load factors, speeds, store requirements); and 4) other various typical functional requirements such as: a) hardpoints for external stores, landing gear, and control surfaces; and b) provisions for electrical, hydraulic, and mechanical control systems.

It was desired that the structure to be studied be derived from a modern, lightweight fighter type of aircraft in about the 15,000-25,000 lb gross-weight class. This generally corresponds to a system designed primarily for the air-superiority mission role.

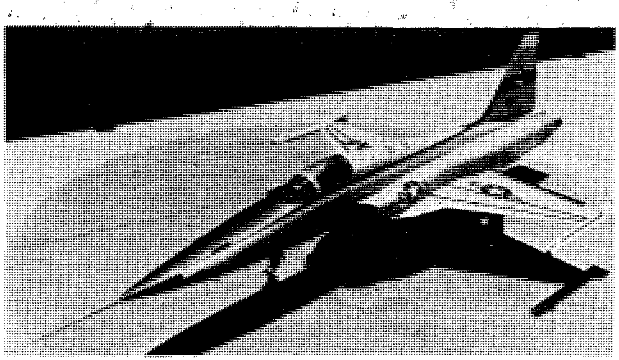

**Fig. 1 F-5E Air Superiority Fighter.**

Presented as Paper 74-337 at the AIAA/ASME/SAE 15th Structures, Structural Dynamics and Materials Conference, Las Vegas, Nevada, April 17-19, 1974; submitted April 15, 1974; revision received January 29, 1975. Work was performed under Contract F33615-72-C-1891 (Project 486U). The authors wish to acknowledge the assistance given by C. E. Beck who served as Air Force Technical Monitor on this program.

Index categories: Aircraft Structural Design (including Loads); Aircraft Structural Materials; Structural Design, Optimal.

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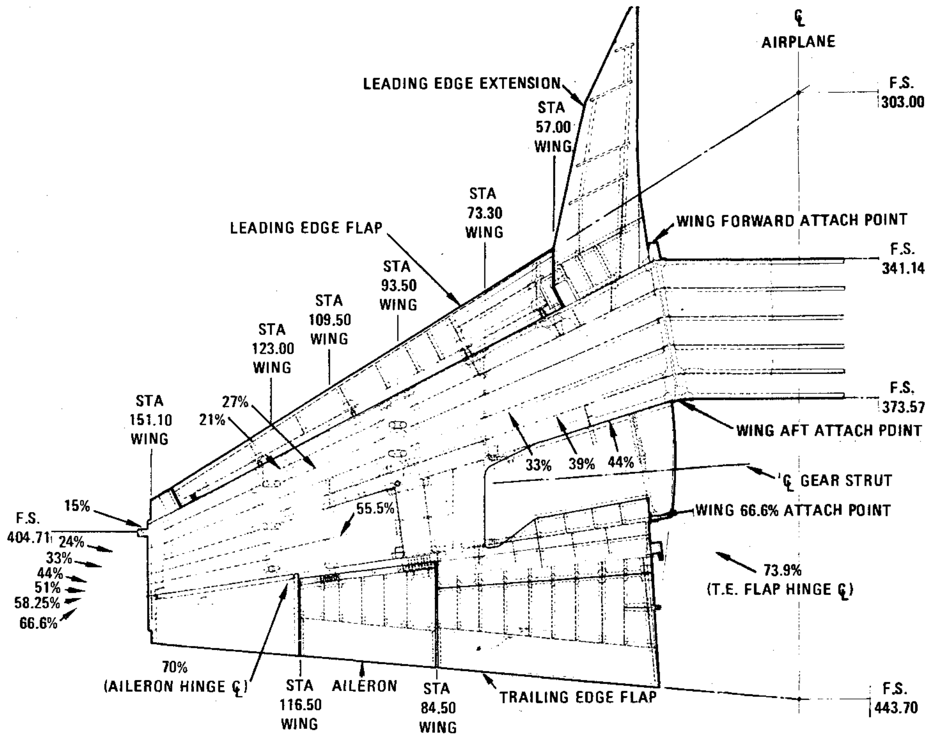


**Fig. 2 F-5E Wing panel structural arrangement.**

The Northrop F-5E Air Superiority Fighter (15,000-20,000 lb gross weight) was selected as the baseline to provide realistic functional, structural, and operational requirements and constraints for the study (Fig. 1). The specific component examined was the main wing box and carrythrough structure. The baseline aircraft structural box is "dry," continuous from tip to tip (25.2 ft), has maximum depth of 5.8 in., and is designed for a maximum load intensity of 24,000 lb/in. The structural box is essentially an all-aluminum alloy, has external stores provisions at the tips and 2 other stations per panel, is designed to the MIL-A-8860 series of structural design criteria specifications, and weighs approximately 1,000 lb.

The F-5E wing panel, as shown in Fig. 2, consists of the main box structure including carry-through, leading-and trailing-edge flaps, ailerons, leading-edge extensions, and trailing-edge panels. The main landing gear is in the inboard portion of the wing and attached to the rib at wing station (W.S.) 73.3 and inboard portion of the 44% spar. External store capabilities are provided at the wing tips and by jettisonable pylons at W. S. 93.5 and W. S. 123.0. The wing panel is a single piece structure extensing continuously from tip to tip with no cover splices. The wing attaches to the fuselage at six points: two each at the 15%, 44%, and 66.6% spars—the former two locations being the primary attachments and the latter (66.6%) being a "secondary" shear tie attachment.

The main wing box is a thick-skin, multi-spar, all-aluminum structure except for steel ribs supporting the landing gear and wing tip stores. As noted previously, the wing is attached to the fuselage through 6 shear-type fittings. The fittings at the 15% and 44% spars are integral parts of 2 canted, forged ribs located at the wing-fuselage intersection line.

The structural materials utilized in the baseline wing box are shown in Table 1. Various upper and lower skin panels, as well as the outer trailing edge consist of honeycomb panels with 7075-T6 face sheets.

The baseline F-5E wing structure (Fig. 3) was designed prior to the existence of the current USAF damage tolerance criteria. These criteria were applied to applicable portions of the baseline wing structure to "update" this structure to these requirements. The objective of this study was to estimate the weight and cost of a production state-of-the-air wing which would be directly comparable, criteria-wise, to the advanced concepts studied in this program. It is not the purpose of this paper to discuss the damage tolerance requirements, except to say that the baseline structure does indeed meet these requirements, and therefore no weight penalty is incurred in "updating" the baseline.

**Table 1 Structural materials utilized in the baseline wing box of the F-5E wing panel**

| | |
|---|---|
| Upper skin | 7075-T651 |
| Lower skin | 7075-T7351 |
| Spars | 7075-T73 and T76 extrusions |
| | 7049-T73 forging |
| | 7175-T736 forging |
| Ribs | 7075-T73 forging |
| | 7175-T736 forging |
| | Hy-Tuf steel forging |
| | 4140 steel forging |

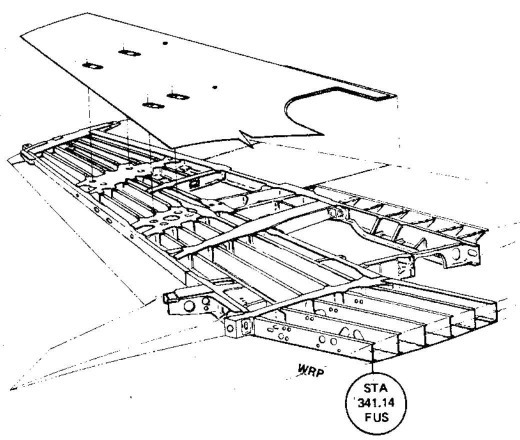


**Fig. 3 Baseline F-5E wing.**

## Design Approach

An essential part of the program was the approach used in obtaining the various design concepts. Figure 4 shows the

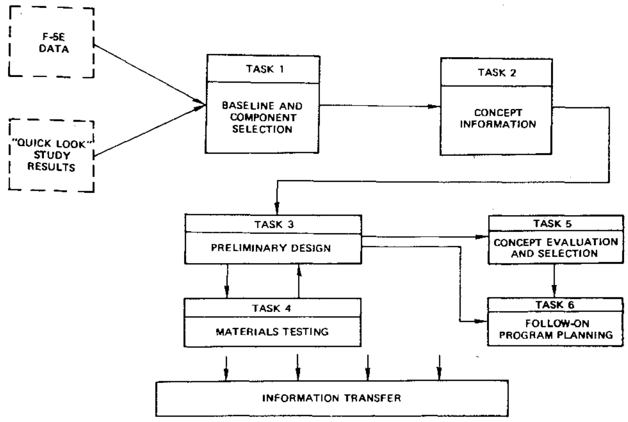


**Fig. 4 Program approach flow chart.**

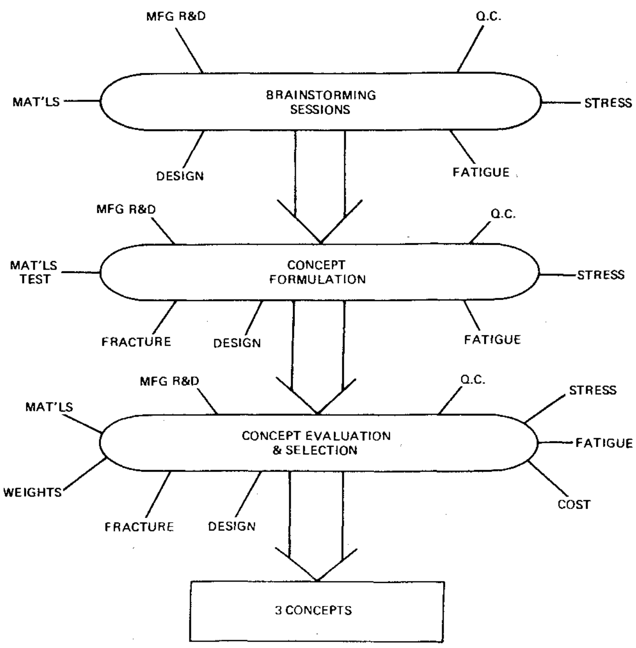


**Fig. 5 Discipline interaction.**

program approach in schematic form. Basic F-5E data are combined with the results of the previously completed "quick-look" study[1] and used as a starting point for this study. The study was divided into 6 tasks, going from "Baseline and Component Selection" to "Follow-on Program Planning."

However, the key to the success of the ADP approach was the complete interaction of all the technical disciplines at the outset. Representatives from design, stress analysis, fatigue and damage tolerance analyses, manufacturing R&D, quality control, weights analyses, and cost analysis all met in brainstorming sessions, where ideas on either the component or assembly level were conceived, discussed, accepted, or rejected. The philosophy was to arrive at an acceptable design from a strength and weight viewpoint at the lowest cost possible, rather than "whatever the cost turns out to be." Figure 5 shows the sequence of design development in more detail, particularly how the discipline interaction affects the final 3 choices, required by terms of the program.

## Materials Test Program

A major materials test program was undertaken to support the design and analytical efforts. Several newer aluminum and titanium alloys were tested, most notably amongst these 7050 and 7475 aluminum, and Ti 6Al-4V$\beta$MA and Ti 6Al-2Sn-2Mo-2Cr-2Zr-0.25Si. Of particular interest were the $K_{Ic}$ and $K_{Iscc}$ tests. For a description of this test program, the reader is refferred to AFFDL-TR-73-52, Vol. III.[2]

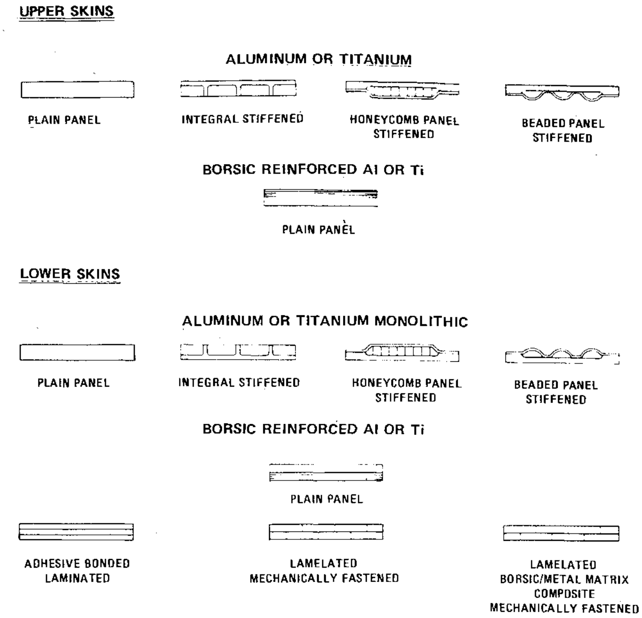


**Fig. 6 Wing skin concepts.**

## Cost Analysis

The cost analysis for the program was an intergral part in the design decision process for recommending designs for further development. As such the cost estimates were developed from preliminary manufacturing plans and engineering drawings. Close coordination was maintained among the cost analysis, engineering, and manufacturing disciplines throughout the study. Cost estimates were developed and iterated as design improvements were made or as new information about manufacturing technology became available.

To perform the cost comparison of the advanced metallic structure designs with the baseline, a uniform cost element structure was developed. This cost element structure provided a rational breakdown for the collection and presentation of cost data.

The initial breakdown separated recurring and nonrecurring costs. Each of these was further divided by labor and material functions. All engineering, tooling, planning, testing, quality control, and manufacturing operations were accounted for.

Some of the ground rules applied were: a) quantity of 300 units in production with a full complement of production tools; b) a typical industry improvement curve of 79% with a variance factor of 1.45 at $T_{1000}$; c) both labor and materials escalated to 1977 dollars; and d) consideration given to the expected advancement in the state-of-the-art in titanium technology by 1977.

## Designs

The initial design effort concentrated on 2 principal areas. The first was an in-depth cost-weight tradeoff of 8 different methods of spar construction. These were expanded to 21 spar concepts, when the additional variable of material was introduced.

The second study was of wing cover construction approaches. Multi-member, single member, external stiffening, integral stiffening, spar spacing, and material were the variables considered in this study. An illustration of the initial wing skin concepts contemplated in this program is shown in Fig. 6.

Through a process of elimination the choice of spar and skin ideas was narrowed considerably. A large number of complete wing concepts was then reduced to the 9 concepts, for which the concept/material matrix is shown in Table 2.

This paper will limit itself to a discussion of the 3 chosen

Table 2 Advanced metallic structural concept material matrix

| | CONCEPT NO. 1 Ti. FULL DEPTH H.C. CORE | CONCEPT NO. 1A Al. FULL DEPTH H.C. CORE | CONCEPT NO. 3 Al/Ti 6-SPAR | CONCEPT NO. 3A Al/Ti WELDED 6-SPAR | CONCEPT NO. 4 H.C. PANEL 5-SPAR | CONCEPT NO. 5 H.C. PANEL 4-SPAR | CONCEPT NO. 6/7 Ti-BORSIC/GEODESIC | CONCEPT NO. 8 Al PREC. FORGED 6-SPAR | CONCEPT NO. 8A Al INTEGRAL WEB 6-SPAR | CONCEPT NO'S 1, 4, 5, AND 6/7 WINGTIP | CONCEPT NO. 1A WINGTIP | CONCEPT NO. 3 WINGTIP | CONCEPT NO. 3A WINGTIP | CONCEPT NO. 8 WINGTIP | CONCEPT NO. 8A WINGTIP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UPPER SKIN | Ti-6-22-22 STA PLATE | 7050-T7651 PLATE | 7050-T7651 PLATE | 7050-T7651 PLATE | Ti-6-22-22 STA PLATE | Ti-6-22-22 STA PLATE | Ti-BORSIC | 7050-T7651 PLATE | 7050-T7651 PLATE | Ti-622-22 STA SH | 7050-T7651 PLATE | ← | — | → | 7050-T7651 PLATE |
| LOWER SKIN | Ti-6Al-4V BMA PLATE | 7475-T7651 PLATE | Ti-6Al-4V BMA PLATE | ← | → | Ti-6Al-4V BMA PLATE | Ti-6Al-4V BMA LAM SH | 7475-T7651 PLATE | X2048-T736 PLATE | Ti-6-22-22 STA SH | 7475-T7651 SHEET | 7050-T7651 PLATE | Ti-6Al-4V BMA PLATE | 7475-T7651 SHEET | X2048-T851 PLATE |
| 15% SPAR | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | ← | — | → | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. |
| 44% SPAR | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | ← | — | → | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. | N/A | N/A | 7075-T73 SHEET | Ti-6Al-4V BMA SHEET | 7075-T73 SHEET | 7075-T73 SHEET |
| 66% SPAR | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | ← | — | → | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. | Ti-6Al-4V BMA P.F. | 7050-T736 P.F. | 7050-T736 P.F. |
| INTERIOR SPARS | N/A | N/A | Ti-6Al-4V BMA SHEET | ← | — | → | Ti-6Al-4V BMA SHEET | 7050-T736 P.F. | 7050-T736 P.F. | N/A | N/A | 7075-T73 SHEET | Ti-6Al-4V BMA SHEET | N/A | N/A |
| ROOT RIB | Ti-6-22-22 STA P.F. | 7050-T736 P.F. | Ti-6-22-22 STA P.F. | ← | — | → | Ti-6-22-22 STA P.F. | 7050-T736 P.F. | 7050-T736 P.F. | N/A | ← | — | — | → | N/A |
| GEAR RIB (W.S. 73.3) | Ti-6-22-22 STA P.F. | ← | — | — | — | — | — | → | Ti-6-22-22 STA P.F. | N/A | ← | — | — | → | N/A |
| INBOARD PYLON RIB (W.S. 93.5) | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | 7175-T736 H.F. | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | 7175-T736 H.F. | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | 7175-T736 H.F. | N/A | ← | — | — | → | N/A |
| OUTBOARD PYLON RIB (W.S. 123.0) | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | 7175-T736 H.F. | Ti-6Al-4V ANN CSTG | ← | → | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | 7175-T736 H.F. | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | Ti-6Al-4V ANN CSTG | Ti-6Al-4V ANN CSTG | 7175-T736 H.F. | 7175-T736 H.F. |
| TIP RIB | Ti-6Al-4V ANN CSTG | ← | — | — | — | — | — | — | — | — | — | — | — | → | Ti-6Al-4V ANN CSTG |
| HONEYCOMB CORE UPPER | N/A | ← | → | N/A | 5056 Al 4.4 #/FT$^3$ | 5056-Al 4.4 #/FT$^3$ | N/A | ← | — | — | — | — | — | → | N/A |
| HONEYCOMB CORE LOWER | N/A | ← | → | N/A | 5056 Al 3.1 #/FT$^3$ | 5056-Al 3.1 #/FT$^3$ | N/A | ← | — | — | — | — | — | → | N/A |
| HONEYCOMB CORE FULL DEPTH | 5056 Al 3.1 #/FT$^3$ | 5056-Al 3.1 #/FT$^3$ | N/A | ← | — | — | — | → | N/A | 5056 Al 3.1 #/FT$^3$ | N/A | ← | — | → | N/A |

Table 3 Concept ranking procedure

| | EFFICIENCY | | TECHNOLOGY ADVANCEMENT | | | | INTEGRITY | | | | "ILITIES" | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WEIGHT | COST | CONCEPTS | MANUFACTURING | MATERIALS | FRACTURE | STATIC | FATIGUE | SAFE CRACK | FAIL SAFE | INSPECTABILITY | MANUFACTURABILITY | MAINTAINABILITY | REPAIRABILITY | PREDICTABILITY |
| CONFIG. / Weighting Factor | .15 | .15 | .09 | .09 | .09 | .03 | .03 | .09 | .09 | .09 | .05 | .02 | .01 | .01 | .01 |
| GRADE | | | | | | | | | | | | | | | |
| SCORE | .30 | | .30 | | | | .30 | | | | .10 | | | | |

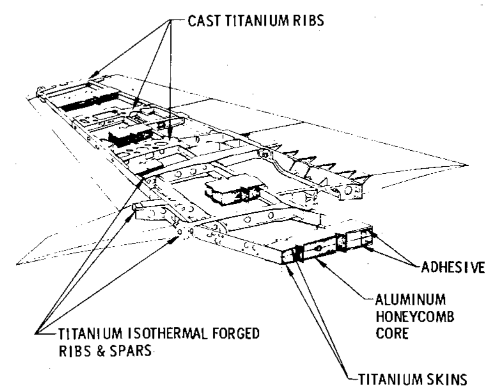


**Fig. 7 Full-depth bonded honeycomb core wing.**

concepts. However, prior to that discussion, it is necessary to discuss the criteria by which the various concepts were compared, not only against each other, but also against the baseline. A "concept ranking" scheme was devised for this purpose, the concept of which is shown in Table 3. It is noted here that "efficiency," which includes cost and weight, is assigned 30% weighting factor, as is "technology advancement" and "integrity," and the "ilities" group is assigned 10% weighting factor. Table 3 shows the further breakout below these 4 main headings.

### Full-Depth Honeycomb Wing

This design concept is one of the "quick-look" designs selected for further and more detailed study in this program, since it was the lightest and most torsionally rigid design in the "quick-look" study.[1]

This concept (Fig. 7) consists of 9 full-depth aluminum honeycomb core bays adhesively bonded to machine-tapered titanium plate skins. These skins are procured in one piece, rough cut to shape, resulting in substantial material cost savings over the purchase of rectangular plate stock. The substructure is made entirely of titanium to eliminate the presence of any bond preloading caused by bonding materials of different coefficients of thermal expansion. The primary wing interior structure comprises 3 main spars and 5 ribs, which are all designed to slow crack growth criteria.

The peripheral spars, the wing attach rib and landing gear rib are all precision forged in titanium. The inboard pylon rib, outboard pylon rib and the tip rib are all precision titanium castings.

### Welded Six-Spar Wing

This design (Fig. 8) attempts to exploit to advantage the weldability of titanium alloys in the one design concept where titanium is used extensively without adhesive bonding. The principal advantages are improved fatigue and crack growth allowables through the elimination of all fasteners through the lower skin in the critical areas, and increasing the efficiency of the lower wing bending material by placing it as close to the lower wing outer mold line as possible.

This concept was originally formulated to take advantage of the increased specific fatigue strength and fracture toughness of titanium in the wing areas where these design aspects are most critical. Additionally, this concept as conceived was to represent the lowest cost and least risk utilization of titanium in the concepts under study in this program.

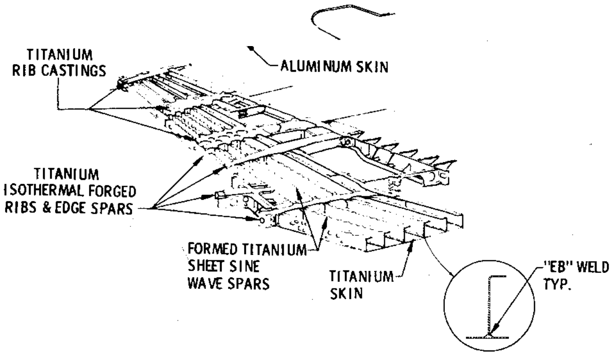


Fig. 8 Welded 6-spar wing.

The concept initially consisted of a titanium lower wing skin with spanwise beaded panels bonded to its inner surface. It was thought that this method of stiffening a titanium lower skin, though rather inflexible in application, would be the most cost effective method of utilizing applied stiffening to a titanium wing skin. Because of the limited applicability of this type of stiffening its employment was limited to the lower skin of a 6 spar wing.

The resulting wing is similar in planform to the baseline wing. As the upper wing skin was not critical from a crack growth standpoint, and the wing possesses the spar spacing necessary for adequate upper skin support, a 7050-T7651 aluminum alloy plate was used for the upper skin of this configuration. The use of titanium in this design is confined to the area where fracture toughness is of prime importance. It became evident during the second iteration of the stress analysis that if the quantity of material used for the beaded inner pans is added instead to the outer wing skin thickness, the compressive stability of these thicker panels is greater than the beaded panels originally considered. Therefore a plain machined Ti-6Al-4V$\beta$MA plate lower skin replaced the beaded stiffened skin.

The interior spars are of formed Ti-6Al-4V$\beta$MA sheet and are employed outboard to the outboard pylon rib. The interior wing spars outboard of the outboard pylon rib are Ti-6Al-$\beta$MA formed sheet without web corrugation.

The substructure is T.I.G. weld assembled and then the lower wing skin is electron beam welded to this substructure. When the X-ray inspection, stress relieving and straightening have been completed, the upper 7050-T7651 aluminum skin is attached to the welded structure with blind fasteners. The lower skin is welded to the substructure from root to tip.

Assembly of the substructure and lower wing skin by welding considerably alters the substructure cost. This alteration manifests itself principally in the decreased complexity of the Ti-forgings and castings that constitute the bulk of the substructure. These details which were formerly channels or "i" beams with both inner mold lines contained on the part are now "tees" or angle cross-sectioned parts containing only the upper inner mold line of the wing. This eliminates the major close tolerance dimension on these parts reducing the risk factor in procuring these parts as well as lowering their cost and reducing the amount of subsequent machining required (die lock is eliminated). However, there can no longer be any aluminum substructure details as all these interior members are welded to the lower skin.

#### Precision Forged Substructure Wing

This design (Fig. 9) is a further refinement of the lowest cost "quick look" design. It is similar in planform to the baseline wing structure. It differs in several aspects, however. The first is the substitution of more advanced aluminum alloys in the various structural elements of the wing. Titanium has been used in place of steel for the landing gear rib and the tip rib. The latter is a Ti-6Al-4V annealed casting; the former being a Ti-6-22-22 STA forging. The second principal difference of this design is the precision forging of all the aluminum substructural elements. Finally, corrugating the spar webs, the source of a 17-lb weight saving at a minimal increase in die cost, complete the specific variances from the baseline wing structure.

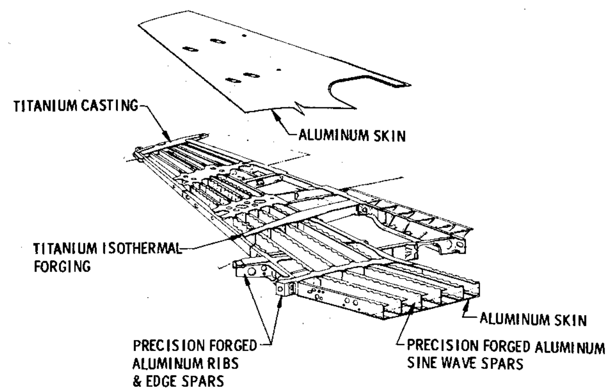


Fig. 9 Precision forged substructure wing.

Table 4 Weight and cost summary

| Concept | Description | Weight change | Cost change |
|---|---|---|---|
| 1 | full-depth H/C (Ti) | −11% | +28% |
| 1A | full-depth H/C (Al) | − 6% | −15% |
| 3 | Al/Ti 6-spar | − 5% | +37% |
| 3A | Al/Ti 6-spar, welded | − 7% | +38% |
| 4 | 5-spar H/C stiffened | −10% | +62% |
| 5 | 4-spar H/C stiffened | −11% | +56% |
| 8 | 6-spar Al | −11% | −25% |
| 8A | 6-spar Al, int-web | −11% | −13% |

This design again proves to be the most economical of the concepts under investigation, realizing a 25% cost reduction. It achieves an 11% weight saving and also poses the least risk of all the concepts considered.

## Summary

Table 4 shows a summary of cost and weight of eight different concepts. Concept 6/7 (Table 2) was not carried this far, since early estimates showed Ti to be both heavier and more expensive than the baseline. Of the three chosen concepts, Numbers 1 and 8 are the lightest, and No. 8 is the least expensive.

## Concept Ranking

Table 5 shows the implementation of the concept ranking scheme, which was discussed earlier. All terms were graded on a scale of 1.0-10.0. For example, with respect to weight, the lightest scores 10.0 and the heaviest scores 1.0 irrespective of whether or not it is heavier or lighter than the baseline design.

A concept, designated as 6/7, comprised a Ti-Borsic upper skin, a geodesic lower skin and a four-spar titanium substructure. Although this concept scored very well (4.70) in the areas of "technology development," "integrity" and "ilities," it was eliminated from further consideration as previously discussed.

The 3 chosen concepts were: No. 1—full-depth honeycomb with titanium skins (this scored highest on the rating chart); No. 3A—aluminum/titanium six-spar wing with extensive use of welding on the bottom skin (this scored second highest on the rating chart); and No. 8—aluminum six-spar wing (this scored third highest on the rating chart). Although Concept No. 1A (full-depth honeycomb with aluminum skins) scored a tie with Concept No. 8, No. 1A was eliminated because it is a variation of No. 1, and does not offer the cost and weight savings represented by No. 8.

**Table 5 Concept ranking**

| | | EFFICIENCY | | | TECHNOLOGY ADVANCEMENT | | | INTEGRITY | | | | "ILITIES" | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CONFIGURATION | WEIGHTING FACTOR | WEIGHT | COST | CONCEPTS | MANUFACTURING | MATERIALS | FRACTURE | STATIC | FATIGUE | SAFE CRACK | FAIL SAFE | INSPECTABILITY | MANUFACTURABILITY | MAINTAINABILITY | REPAIRABILITY | PREDICTABILITY | |
| | | .15 | .15 | .09 | .09 | .09 | .03 | .03 | .09 | .09 | .09 | .05 | .02 | .01 | .01 | .01 | 1.00 |
| Baseline | GRADE | 1.0 | 7.41 | 1 | 1 | 1 | 10 | 5.5 | 3 | 3 | 1 | 5 | 8 | 6 | 5 | 10 | |
| | SCORE | .15 | 1.11 | .09 | .09 | .09 | .30 | .16 | .27 | .27 | .09 | .25 | .16 | .06 | .05 | .10 | 3.24 |
| #1 Full Depth Honeycomb Ti | GRADE | 10.0 | 4.52 | 9 | 8 | 8 | 5 | 5.5 | 7.5 | 7.5 | 1 | 2 | 3 | 6 | 2 | 4 | |
| | SCORE | 1.50 | .68 | .81 | .72 | .72 | .15 | .16 | .68 | .67 | .09 | .10 | .06 | .06 | .02 | .04 | 6.47 |
| #1A Full Depth H/C Aluminum | GRADE | 5.74 | 8.97 | 5 | 6 | 4 | 5 | 5.5 | 7.5 | 7.5 | 1 | 2 | 4 | 6 | 2 | 6 | |
| | SCORE | .86 | 1.35 | .45 | .54 | .36 | .15 | .16 | .68 | .67 | .09 | .10 | .08 | .06 | .02 | .06 | 5.62 |
| #3 Al-Ti 6-Spar | GRADE | 4.87 | 6.17 | 4 | 7 | 5 | 10 | 5.5 | 3 | 3 | 1 | 5 | 5 | 6 | 5 | 7 | |
| | SCORE | .73 | .93 | .36 | .63 | .45 | .30 | .16 | .27 | .27 | .09 | .25 | .10 | .06 | .05 | .07 | 4.72 |
| #3A Al-Ti Welded 6-Spar | GRADE | 6.53 | 3.48 | 6 | 9 | 5 | 7 | 5.5 | 10 | 10 | 1 | 6 | 3 | 6 | 1 | 5 | |
| | SCORE | .98 | .52 | .54 | .81 | .45 | .21 | .16 | .90 | .90 | .09 | .30 | .06 | .06 | .01 | .05 | 6.04 |
| #4 5-Spar Honeycomb | GRADE | 8.89 | 1.0 | 7.5 | 8 | 6 | 10 | 5.5 | 3 | 3 | 1 | 3 | 4 | 6 | 5 | 5 | |
| | SCORE | 1.33 | .15 | .68 | .72 | .54 | .30 | .16 | .27 | .27 | .09 | .15 | .08 | .06 | .05 | .05 | 4.90 |
| #5 4-Spar Honeycomb | GRADE | 9.92 | 1.62 | 7.5 | 8 | 6 | 10 | 5.5 | 3 | 3 | 1 | 3 | 4 | 6 | 5 | 5 | |
| | SCORE | 1.49 | .24 | .68 | .72 | .54 | .30 | .16 | .27 | .27 | .09 | .15 | .08 | .06 | .05 | .05 | 5.15 |
| #8 Al-Al 6-Spar | GRADE | 9.29 | 10.0 | 2 | 5 | 4 | 10 | 5.5 | 3 | 3 | 1 | 5 | 10 | 6 | 5 | 9 | |
| | SCORE | 1.39 | 1.50 | .18 | .45 | .36 | .30 | .16 | .27 | .27 | .09 | .25 | .20 | .06 | .05 | .09 | 5.62 |
| #8A Al-Al 6-Spar Int. Web | GRADE | 9.37 | 8.76 | 3 | 5 | 4 | 7 | 5.5 | 3 | 3 | 1 | 5 | 6 | 6 | 3 | 8 | |
| | SCORE | 1.41 | 1.31 | .27 | .45 | .36 | .21 | .16 | .27 | .27 | .09 | .25 | .12 | .06 | .03 | .08 | 5.34 |

GRADING = 1 - 10 SCORE = W.F. x GRADE

## Conclusions

The work performed under the contract shows that:

1) Specific improvements in the cost and weight of a typical structural wing box for an air superiority fighter can indeed be obtained by combining advanced design concepts, materials, and manufacturing techniques.

2) The integrated, or "synergistic," design approach, as utilized in this structures program, could well be expanded to other subsystem design efforts, for example, propulsion, radar, and telemetry.

3) Several new materials, such as 7475 aluminum alloy and Ti-6Al-4V$\beta$MA, have superior fracture toughness properties and are thus good candidates for lower wing skins, where such properties are required.

4) The significant cost savings are generally obtained by utilizing "net" parts as much as possible, i.e., precision aluminum forgings, and, to some degree, precision titanium castings. Reduced piece count, as obtained via the use of corrugated spars, also has a strong influence.

5) The damage tolerance criteria, as used in this program, are still somewhat vague and need further clarification, before general applicability can be imposed on other programs.

## References

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