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Advanced Design Composite Material Aircraft Study

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The objective of this study was to apply advanced composites to a completely new fighter/attack aircraft in an unconstrained manner, in order to obtain an aircraft which is smaller, lighter, and cheaper than an equivalent advanced metal counterpart. Design criteria and requirements were defined and trade studies performed to identify the preferred air vehicle. A structural arrangement of the selected configuration was established to verify the anticipated weight and cost savings and selected critical structural sections were designed in detail.

I. Introduction

THE objective of the Advanced Design Composite Aircraft (ADCA) program was to define the benefits and ramifications of the unrestrained application of advanced composite materials to a completely new aircraft.

The mission selected for this study is the supersonic penetration interdiction fighter (SPIF) mission. A detailed mission description can be found in the final report on this program.[1] This mission provides a demanding set of requirements and therefore exercises the properties of advanced composites to the fullest, yielding the maximum potential payoff from unrestrained use of the materials.

The scope of this program consisted of the preliminary definition of the lowest weight aerodynamic configuration capable of performing the mission. Detail definition of major structural components was then established in order to verify the structural weight savings utilized to establish the preliminary configuration. Aeroelastic tailoring of the wing in order to achieve the maximum in sustained normal acceleration, and of the fin to improve fin effectiveness and, therefore, aircraft directional stability was also addressed. Finally, a detail design of critical structural areas such as wing, fin, canard, landing gear, and control surface attachments was performed. A weight and cost analysis of the completed vehicle was performed in order to establish the weight and cost saving resulting from the application of advanced composite materials when compared to a 1980 metals aircraft and an aircraft which was originally designed using 1980 metals technology and then substituting advanced composite materials for the metal.

II. Configuration Screening

Configurations capable of performing the desired SPIF mission were evaluated using sizing computer programs. Primary input data included weight reduction factors for advanced composite materials, performance characteristics of candidate engines, mission requirement constants, and gross aerodynamic planform characteristics.

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

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Weight reduction factors (over a 1975 metal aircraft) were obtained from analysis of percentage weight savings vs percentage weight of composite material data from available funded programs and in-house studies. This was done on a component-by-component basis. Values were selected which are associated with low cost (design-to-cost approaches rather than those which achieved maximum weight savings regardless of cost).

Figure 1 shows a typical plot of data from a review of empennage programs and studies. This type data, for each component, was utilized to generate the anticipated weight savings used in the preliminary sizing studies shown in Table 1. This table also includes the anticipated weight savings used to screen the comparative advanced metal designs.

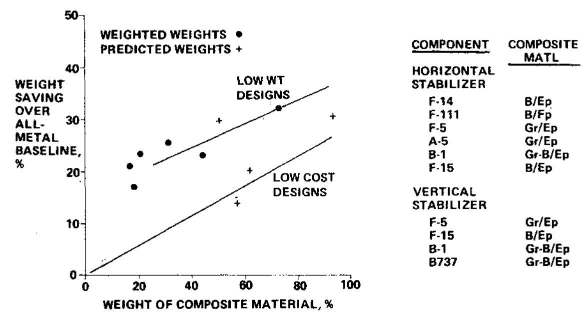

Fig. 1 Advanced composite empennage weight savings.

Table 1 Composite weight reduction factors (% wt saving)

Component	Composites	Advanced metal
Fixed wing:		
No twist cont	28	9
Twist (Λ = 20, 40, 60 deg)	26.5, 23, 17	. . .
Double delta	23.5	. . .
Swing wing:		
No twist cont	20	9
Twist	17	. . .
Tails and canards:		
Slab	23	9
Fixed	30	9
Body	22	3
Air inductor:		
Fixed inlet	20	5
Variable inlet	20	5
Landing gear	16	10

Engine candidates were, by Air Force direction, confined to those presently available or readily derived by 1980. This requirement limited candidates to current or growth versions of existing engines, specifically the F100, J101, F404, F101, and TF30. The TF30 series engines were found to have noncompetitive thrust-to-weight ratios, while the more advanced J101 versions were avoided as they were unlikely to be readily available.

Various aerodynamic configurations with different wing planforms were selected for screening. The delta planform exhibited the best supersonic characteristics, whereas the more conventional transonic swept-wing configuration exhibited the best transonic maneuver capability. The trisonic wing is an optimized combination of the two. Variable sweep was included because it has potential for matching configuration to the various flight regimes.

The results of a typical configuration screening are presented in Table 2 and show the trisonic configuration with either a single F101 or two F404 engines to be the lightest design. The higher weights of the delta are the result of the low wing loadings required to achieve acceptable takeoff and maneuver performance, while the variable sweep aircraft suffers from the difficulties in effectively utilizing composites for such configurations. The transonic configurations are close contenders; however, more detailed studies of both these and the trisonic configurations indicated that the former are somewhat heavier than shown on the figure, whereas the latter appear to be almost 500 lb lighter. It was therefore decided to choose the trisonic configuration. The more detailed studies showed that this configuration was acceptable with either a single F101 or two F404 engines, with both versions almost equal in performance and weight. Selection of the single F101 version was made because this engine is under development and will be fully qualified by 1980.

The general arrangement of the selected ADCA configuration is shown in Fig. 2 and the inboard profile is shown in Fig. 3.

III. Materials Selection

In order to apply advanced composite materials realistically to a vehicle, various factors had to be taken into consideration. The first factor, specified by the Air Force, was material availability in the late 1970's of fully qualified systems. The filament selection therefore included boron and graphite, including pitch-based graphite and boron on carbon, fiberglass, and Kevlar 49. The matrices included the epoxies, thermoplastic materials, polyimides, polyarylsulfones, and polyphenylenes and for higher temperature applications, aluminum matrix.

Provision was made for protection against lightning strike and triboelectric charging by including the weight and cost of either flame-sprayed aluminum or aluminum foil bonded both externally and internally in critical regions of the structure. In addition, the detail design allowables were evaluated and selected to conform to the latest wet allowables. A thermal analysis indicated that for this vehicle, the structural temperatures did not exceed 260°F even in the region of the engine.

Because the study required maximum utilization of composites, only HRP (heat-resistant phenolic), Kevlar 49, or graphite honeycomb core were utilized for sandwich construction. This eliminated potential problems associated with corrosion of aluminum core due to moisture ingress. Fastener corrosion problems were also minimized as only A286 stainless steel or titanium fasteners were permitted in laminates containing graphite.

IV. ADCA Structural Arrangement

The preliminary overall structural arrangement of the ADCA was established and configured in order to: 1) minimize the number of parts, 2) minimize the number of joints, 3) emphasize integral structure, 4) provide the required structural integrity, 5) provide adequate access, 6) permit thru-wing construction, and 7) maximize the advantages of advanced composites.

The aircraft structure is comprised of four major structural assemblies: the wing which is configured as a "thru" box multispar structure continuous from tip to tip; the canard, which is a fully moveable slab surface of full-depth honeycomb construction; the vertical fin which, like the

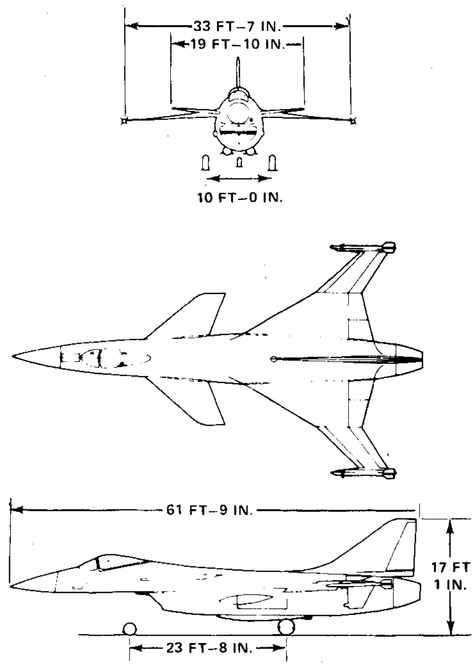

Fig. 2 ADCA configuration.

Table 2 Typical configuration screen for baseline mission[a] ($M = 0.8$-1.6, 35,000 ft)

	Air vehicles									
	Delta		Delta w/retractable canard		Trisonic w/canard		Trisonic w/aft tail		Variable sweep w/aft tail	
Engines[b]	TOGW, lb	Accel. time, s	TOGW, lb	Accel. time, s	TOGW, lb	Accel. time, s	TOGW, lb	Accel. time, s	TOGW, lb	Accel. time, s
F404 (1)	No solution		No solution		No solution		No solution		No solution	
F404 (2)	42,630	110	39,378	83	37,489	72	37,976	73	40,620	83
F404 (3)	45,679	55	45,187	52	44,047	49	44,299	49	47,609	55
F100B (1)	No solution		No solution		No solution		No solution		No solution	
F100B (2)	49,199	59	48,148	55	47,201	52	47,446	52	51,499	59
F101 (1)	45,203	136	39,922	91	37,826	79	37,941	78	41,470	92

[a] Size for most critical of: 3.8 g sustained acceleration @$M = 0.9$, 30,000 ft; 3200-ft takeoff ground roll w/10,000 lb A/G weapons; 3200-ft landing ground roll.
[b] Available or low-cost derivative engines.

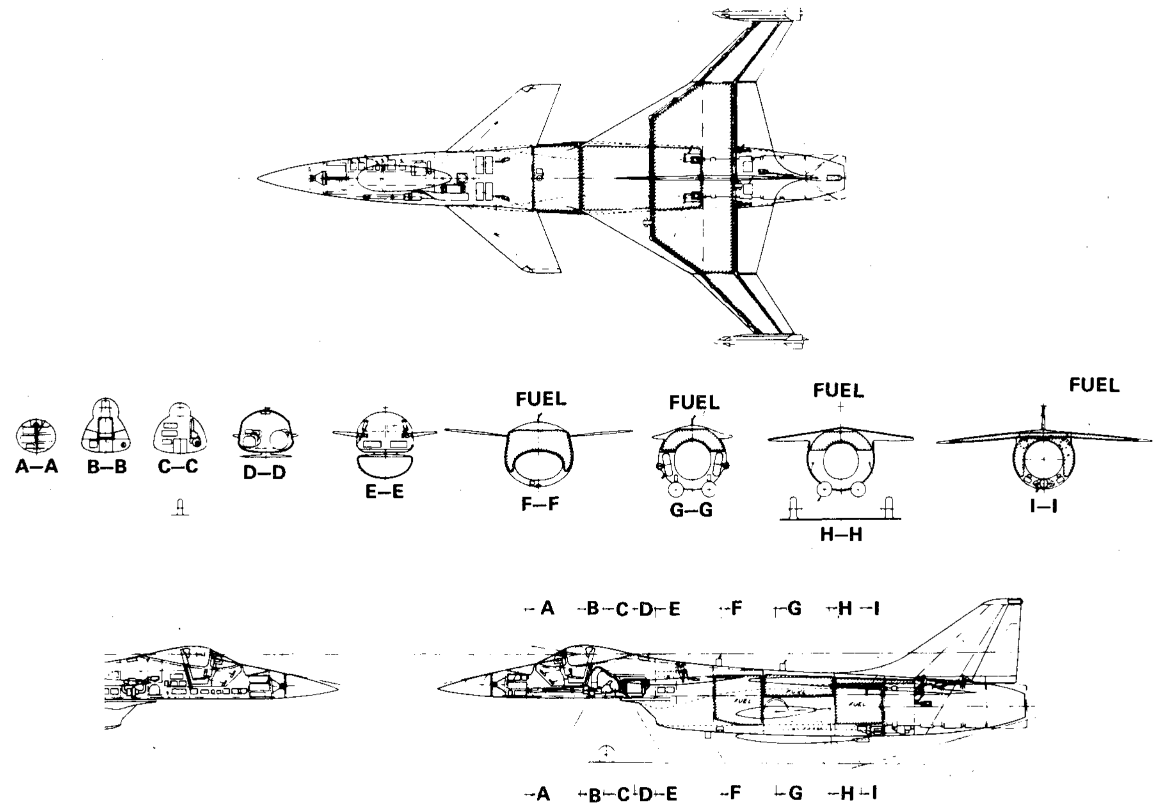

Fig. 3 Inboard profile.

canard, is full-depth honeycomb, and the fuselage which is a semimonoque construction comprising 17 major bulkheads and frames, a structural outer shell, a structural duct, and six longerons.

This design emphasizes large one-piece advanced composite moldings modularized construction, and continuity of structural load paths.

Wing

The ADCA structural wing box is configured as a single-unit multispar structure with a span of nearly 33 ft and a maximum depth of 7.87 in. The structural box doubles as a fuel tank from fuselage station 600 to 701.4 and to B.L. 120.95. The outer panel, from B.L. 120.95 to the tip, is dry. Attachment to the fuselage is accomplished at the front, midmain, and rear spar at B.L. 30.

Based on these design requirements, the in-house developed COMBO (Composite Beam Optimization) program was used to establish that multispar construction was the lightest and most cost-effective form of construction for both the inboard and outboard wing sections. Optimum beam spacing dictated eleven spars for the inboard section and five outboard.

The COMBO program analysis is based on a box beam theory which is modified to incorporate the coupling between bending and twisting that can be induced by anisotropic composite covers. In addition to strength constraints, a torsional stiffness constraint is imposed to insure flutter integrity. The wing structure is idealized as a series of beam segments and the program sizes the cover material and substructure for multispar, full-depth honeycomb core or sheet stringer construction.

The final ADCA wing design concept is shown in Fig. 4. The entire wing structure is fabricated using graphite/epoxy materials, with the exception of the B.L. 120.95 rib and the combination tip rib missile launcher adapter which are titanium parts. The basic concept employs graphite/epoxy spars and ribs attached to one-piece graphite (epoxy skins).

Techniques for aerodynamically optimizing the wing to improve baseline performance were evaluated. The objective

POINT	NUMBER OF PLIES				
	0°	– 30°	– 45°	– 90°	– 135°
1	29	–	8	– 5	– 8
2	46	–	10	– 5	– 10
3	43	–	8	– 5	– 8
4	22	–	11	– 6	– 11
5	38	–	21	– 6	– 21
6	41	–	14	– 6	– 14
7	12	–	15	– 6	– 15
8	30	–	25	– 6	– 25
9	35	–	18	– 6	– 18
10	30	– 60	–	19	– 6
11	28	– 76	–	19	– 6
12	28	– 50	–	19	– 6
13	23	– 30	–	23	– 4
14	20	– 2	–	20	– 2

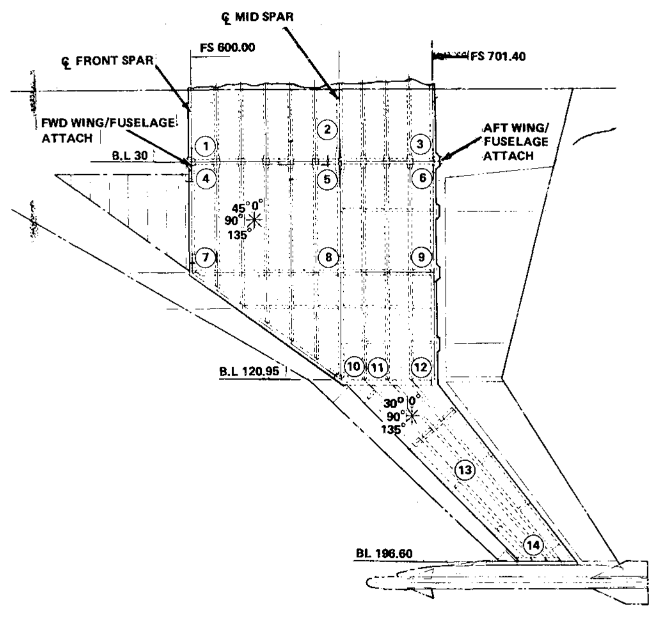

Fig. 4 Wing structure.

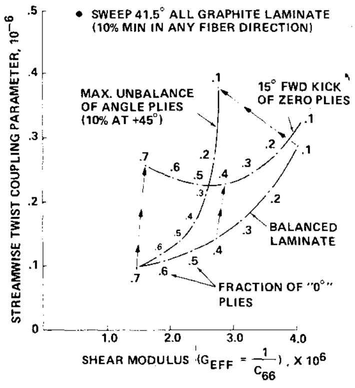

Fig. 5 Wing twist control sensitivity.

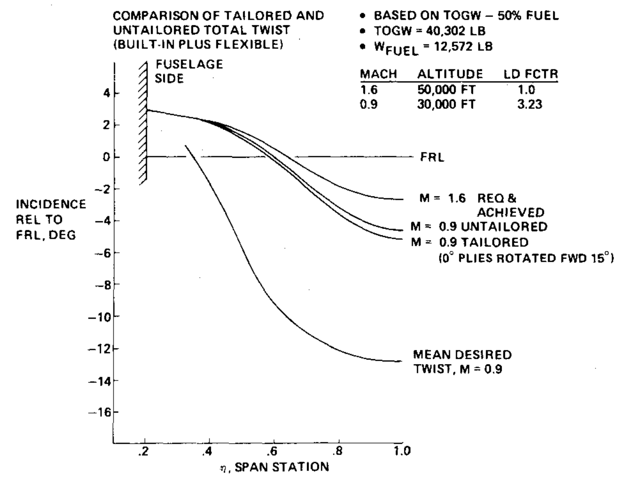

Fig. 6 Ideal wing box twist distribution.

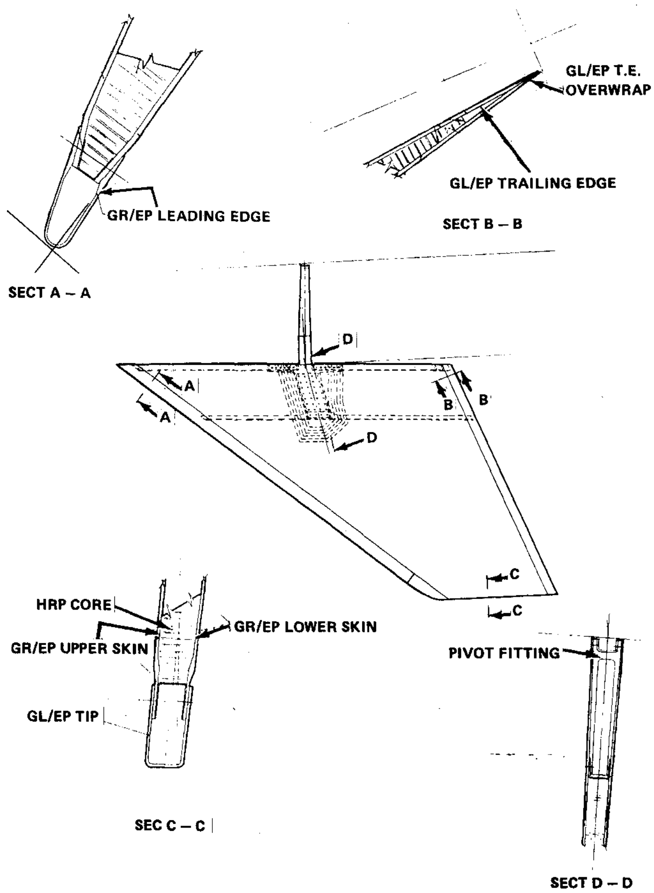

Fig. 7 Canard structural concept.

of this effort was to structurally tailor a wing to match the aerodynamic-wing twist distribution at the supersonic cruise condition and deform under load in such a way as to provide the required optimum wing twist at the transonic sustained maneuver condition. This tailoring was achieved by using advanced composite materials in such combinations and orientations that the resulting laminates are anisotropic, whereby the bending and twisting deformations are coupled. Three practical approaches to achieve this coupling were investigated: 1) unbalancing the $\pm\theta$ deg plies; rotating the entire laminate; and kicking the 0 deg plies through a small angle with the $\pm\theta$ deg plies balanced.

Although the first two of these techniques are effective in coupling the bending and twisting deflections, they both produce a large reduction in the shear stiffness. This resulted in an unacceptable weight penalty for flutter prevention requirements. The concept of kicking off the 0 deg plies does not suffer this penalty. In fact, there is a slight increase in shear modulus and axial strength when the kick angle is less than 15 deg.

A comparison between unbalancing the $\pm\theta$ deg (45 deg) angle plies and kicking the 0 deg plies is presented in Fig. 5 for an all-graphite laminate with a wing sweep of 41.5 deg. The comparison is shown as plots of the twist control parameter against the shear modulus of the laminate. The twist control parameter plotted is a measure of the rate of change in streamwise angle of attack as a result of spanwise bending strain. The curves demonstrate that if the laminate is tensile strength designed, which entails a high percentage of 0 deg plies, as in the ADCA, then kicking the 0 deg plies through a small angle gives a more effective twist control than unbalancing the ± 45 deg plies.

Figure 6 indicates that a 25% increase in tip twist over the untailored wing twist was achieved by rotating the 0 deg plies forward 15 deg. This degree of twist fell far short of the desired aerodynamic twist distribution, also shown in Fig. 6. A wind-tunnel test of these configurations indicated a very small increase in the sustained maneuver capability between an aerodynamically optimum wing twist and an untwisted wing with deflected control surfaces. Because of this, further work to increase the degree of wing twist was not pursued. However, because the slightly higher performance-tailored design could be produced at no increase in weight or cost and no reduction in flutter speed, it was selected for the wing fabrication.

Canard

The canards are fully moveable, independently actuated slab surfaces approximately 80 in. in span and a maximum of 4.4 in. thick at the fuselage side wall. The optimum form of construction, as defined by the COMBO program, is comprised of full-depth honeycomb core supporting an upper and lower skin. To provide attachment to the fuselage, an integral steel shaft root fitting is provided together with two graphite/epoxy redistribution ribs as shown in Fig. 7. The graphite/epoxy skins are bonded to a titanium splice plate which is mechanically attached to the root fitting. An all-bolted design of composite skin to root fitting was also evaluated but was found to be heavier and costlier than the bonded approach for this configuration.

Vertical Fin

The vertical fin is a symmetrical, fixed stabilizing surface from which the moveable rudder is mounted. The fin is approximately 105 in. in span with a maximum depth of 7.4 in. at the root. The main structural box consists of skins, full-depth honeycomb core, three spars, two root ribs, a tip rib, and three intermediate sub ribs located at the rudder hinge points. The primary attachment to the fuselage is at the aft two spars with a shear tie at the forward spar.

The fin structure shown in Fig. 8 is fabricated entirely of advanced composite material with graphite/epoxy channel

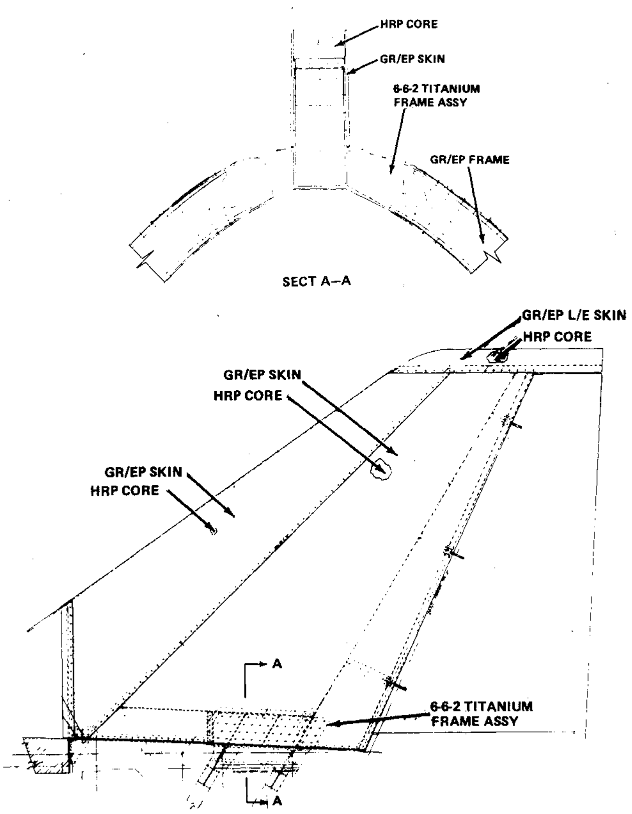

Fig. 8 Fin assembly.

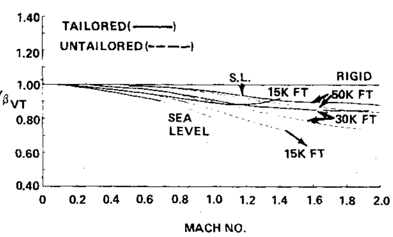

Fig. 9 ($\eta Y_{\beta_{VT}}$) lateral force flexibility factor for vertical tail with rigid rudder.

section spars and skins bonded to and stabilized by full-depth HRP honeycomb core. At the root attachment, the skin is reinforced with boron to improve the material net stress allowable in the presence of high-passing and bolt loads. Attachment to the fuselage is made by mechanical fasteners to a titanium stub frame assembly in the fuselage.

Aeroelastic tailoring studies of the fin indicated significant performance improvement in both flutter speed and fin effectiveness as a result of rotating the spanwise plies 15 deg aft of the box beam reference axis. The remaining ±45 and 90 deg plies were oriented in these directions relative to the box beam reference axis.

An ADCA fin rudder flutter speed analysis indicated a 35% increase in the flutter speed as a result of rotating the spanwise plies aft 15 deg. In addition, a fin effectiveness analysis indicated significant improvements in the fin effectiveness at all altitudes, as shown in Fig. 9. At the critical design case, a 23% increase in the fin effectiveness was realized. This increased effectiveness resulted in a tailored fin that was 18.5 ft^2 smaller than an untailored fin. This resulted in a savings of 589 lb on the takeoff gross weight of the vehicle.

Fuselage

The fuselage is designed primarily by symmetric and asymmetric high-g flight maneuvers and 10 fps landing conditions. The pressurization of the cockpit dictates the

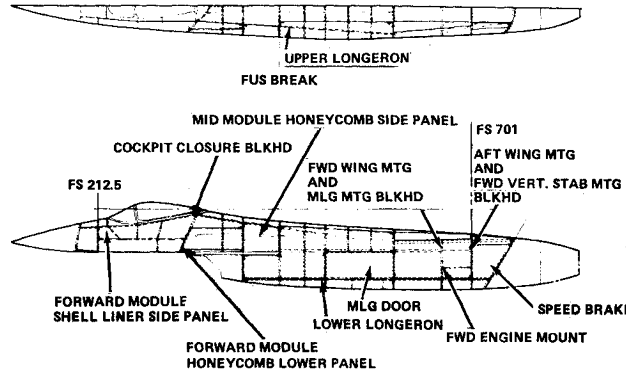

Fig. 10 Fuselage structural concept.

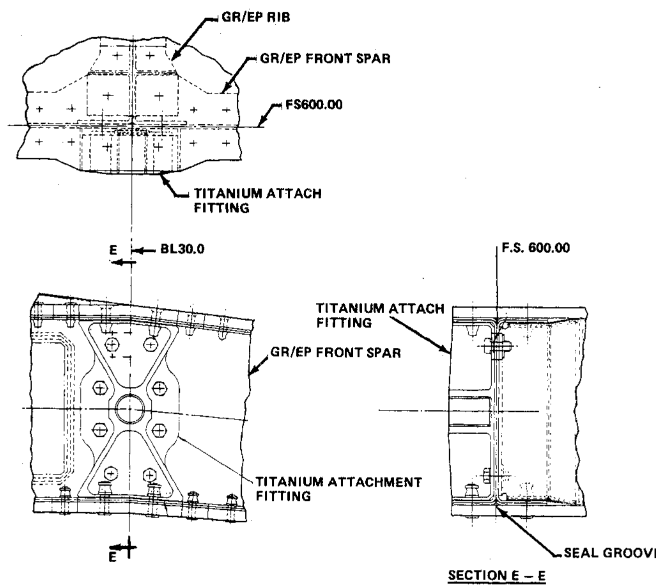

Fig. 11 Wing/fuselage attachment – front spar.

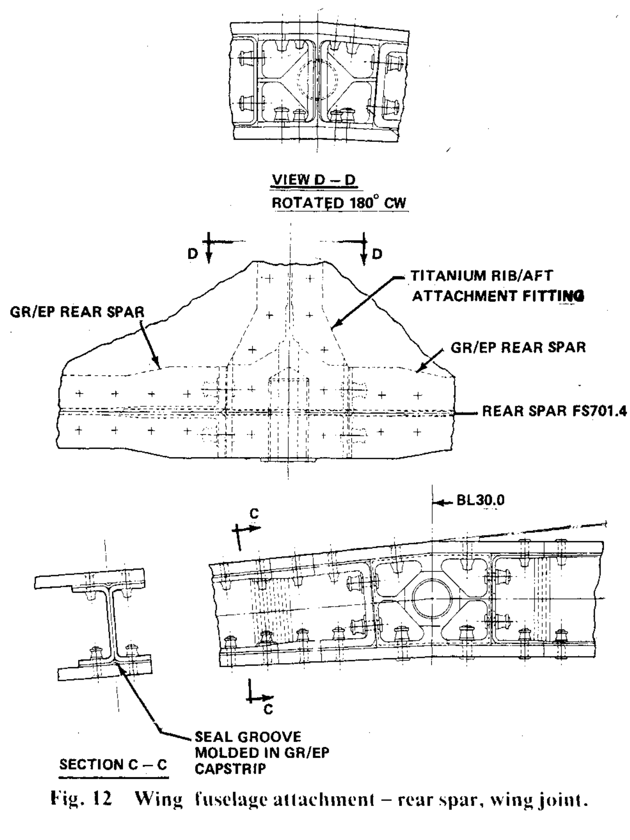

Fig. 12 Wing fuselage attachment – rear spar, wing joint.

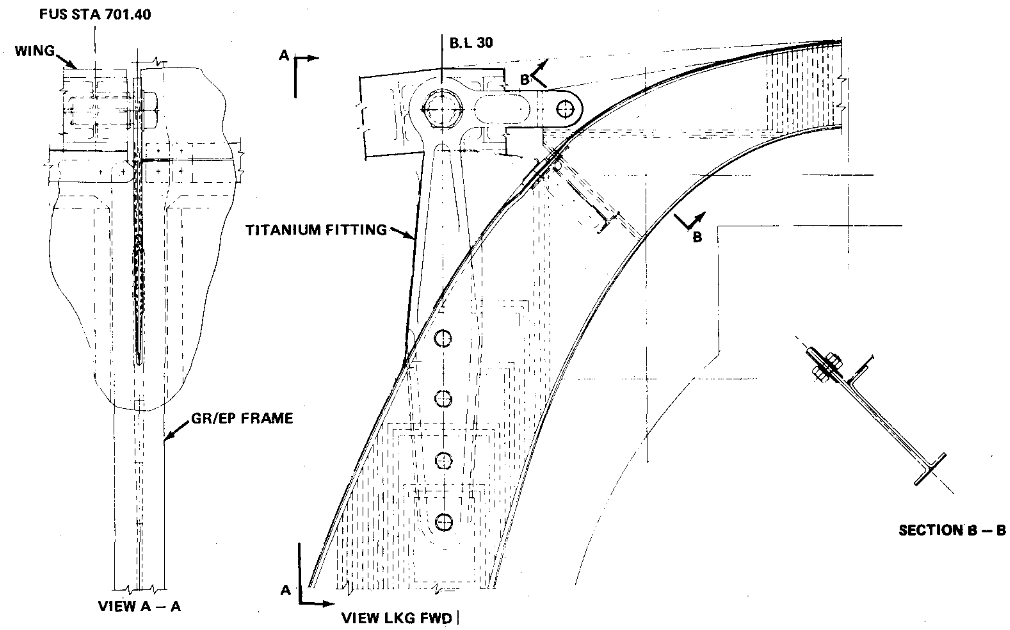

Fig. 13 Wing/fuselage attachment – rear spar, fuselage joint.

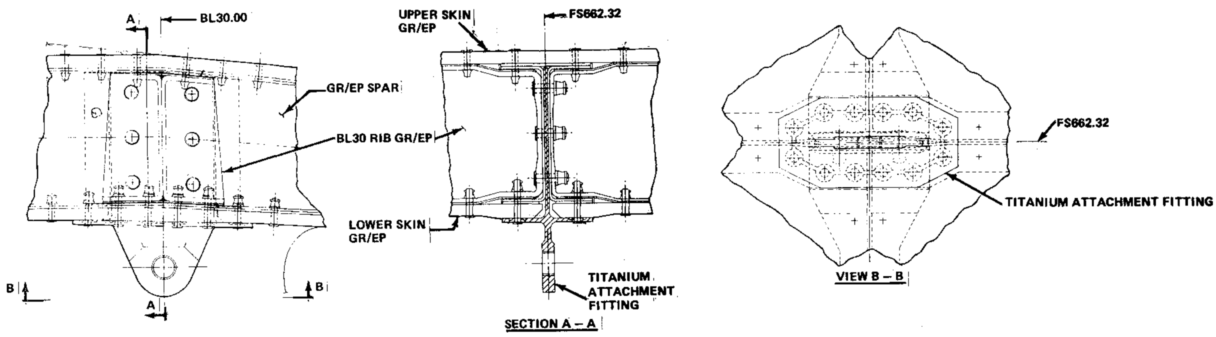

Fig. 14 Wing/fuselage attachment – mid spar, wing joint.

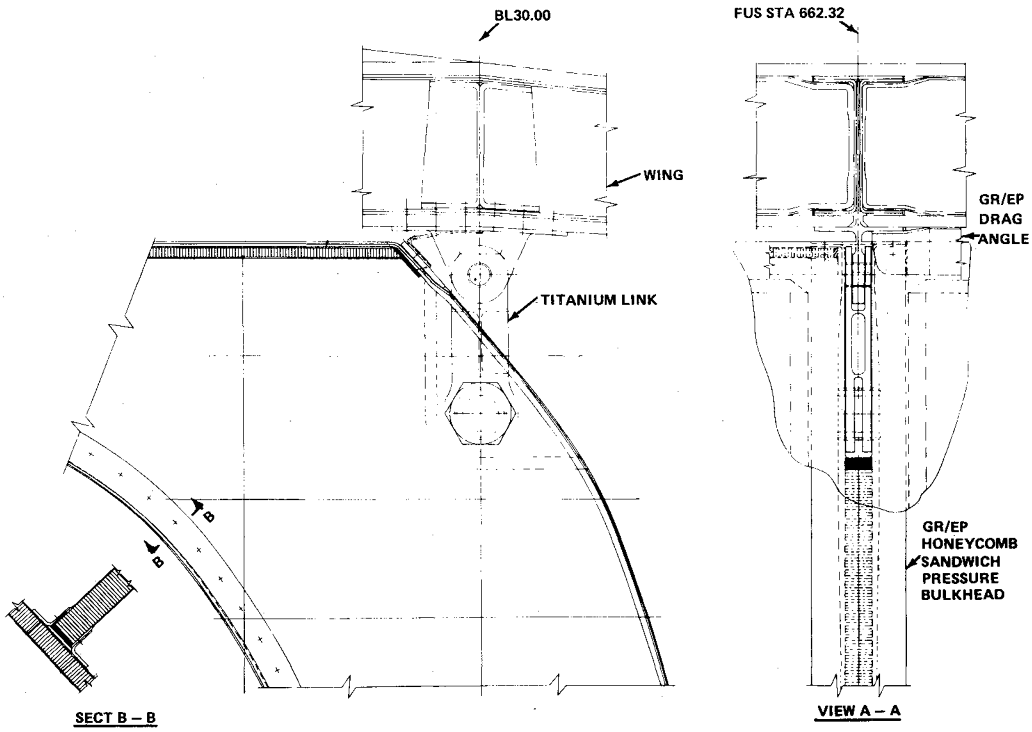

Fig. 15 Wing/fuselage attachment – mid spar, fuselage joint.

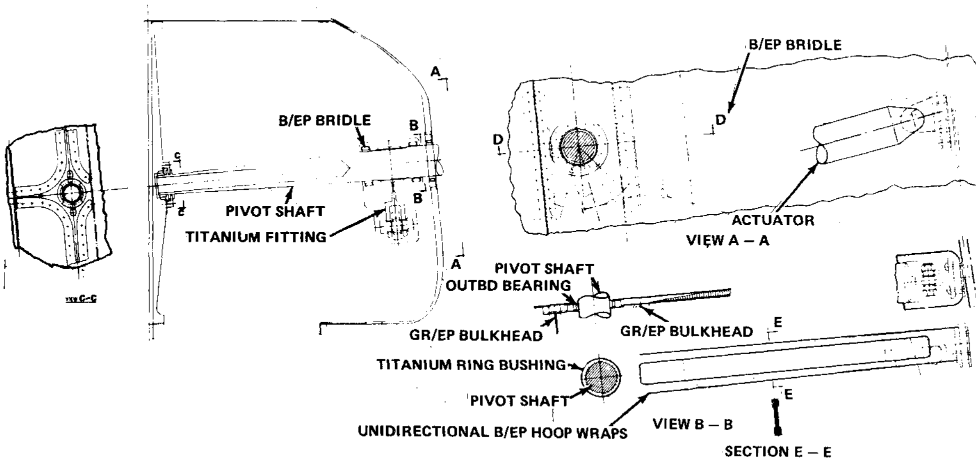

Fig. 16 Canard attachment.

detail design of a large portion of the fuselage. Hinged actuated doors are provided for the nose landing gear and a portion of the forward fuselage structure was designed by hard nose-down landings. Quick opening access doors and panels were required for the gun, gun drum, and avionic equipment.

Fuel tanks occupy most of the volume of the mid and aft fuselage. The surrounding structure was therefore made capable of supporting the fuel tank pressures, which are a combination of constant positive pressurization and pressure caused by maneuver translational and rotational accelerations. The inlet duct structure was designed to withstand the very high inlet pressures associated with hammershock waves generated during engine stalls at high Mach numbers.

The aft fuselage was designed by the extreme engine environment of high temperature and acoustic levels. Consideration was given to fire containment by providing a shield consisting of quartz fibers sandwiched between stainless steel foil around the engine. This shield also considerably reduced the structural temperatures in this region. Access doors were provided for normal engine maintenance; and because engine removal is accomplished by moving the engine directly aft, engine removal doors were not required.

The fuselage structural arrangement is shown in Fig. 10. The fuselage bending moments, both vertical and lateral, are resisted primarily by six longerons (two upper, two lower, and two mid). The fuselage side panels were configured primarily as shear carrying with a low longitudinal modulus but, due to strain compatibility with the integral longerons, a small percentage of the bending moment was transmitted to the shell.

V. Detail Design of Critical Areas

To assure a realistic design, a detail design of certain critical structural joints and details was accomplished. The areas addressed included: 1) wing fuselage attachment, 2) canard fuselage attachment, 3) vertical fin to fuselage attachment, 4) main landing gear attachment, 5) engine mount, 6) aircraft hoist fitting, and 7) control surface attachment.

In general, most of these critical areas utilized metallic fittings to accomplish the splice due to the complex state of stress that exists in these areas.

Wing-to-Fuselage Attachment

The wing fuselage attachment is accomplished at three bulkheads – FS 600, FS 663, and FS 702 – through six attachment points. All points fall on BL 30. In addition to the transfer of large concentrated loads, the avoidance of secondary loads induced by wing deflections must be considered in the design. Replaceability of the fittings was also felt to be an essential feature. The final design met all three of these requirements. The front and rear beam attachment designs, which are basically similar, are shown in Figs. 11-13.

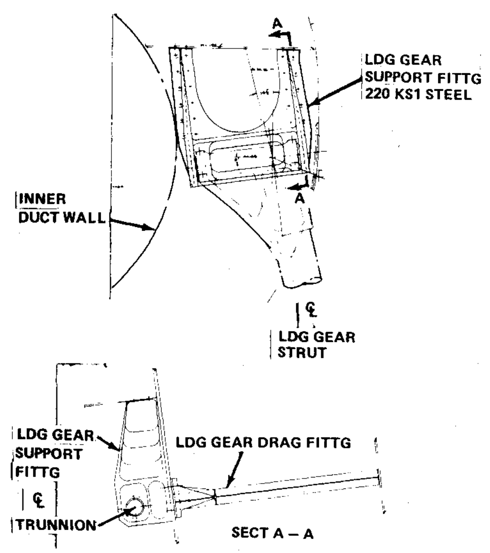

Fig. 17 ADCA main landing gear support installation.

Both designs incorporate steel shear pins located at the neutral axis of the wing to eliminate wing deflection secondary loads.

The midspar attachments, shown in Fig. 14 and 15, are designed to carry vertical loads only. A titanium fitting is sandwiched between the midbeam shear webs and connected by steel bolts. The loads are transferred from this fitting to the graphite/epoxy bulkhead by means of two parallel links. The links eliminate any side loads generated by wing lateral loads or deflection. All-composite wing fuselage attachments were initially evaluated, but it was apparent that the resulting structure would be more complex and less efficient than the utilization to metallic fittings.

Canard-to-Fuselage Attachment

The canard-to-fuselage attachment is shown in Fig.16. Due to the shallow depth of the canard, the bearings were located in the fuselage. The outboard bearing housing is installed in the fuselage side wall at FS 402 and secured by a bolted retaining ring. The canard shaft thrust loads are reacted at the inboard bearing. The vertical bearing loads are beamed to these bulkheads by the fuselage side wall and the centerline keel. The splined actuator arm extends down from the canard shaft and attaches to the forward end of the actuator. The aft end of the actuator is attached to the bulkhead at FS 450. A boron cradle fitting is used to balance the actuator load in a self-balancing system.

Vertical Fin-to-Fuselage Attachment

The vertical fin-to-fuselage attachment is accomplished through the use of a titanium root fitting. The attachment is

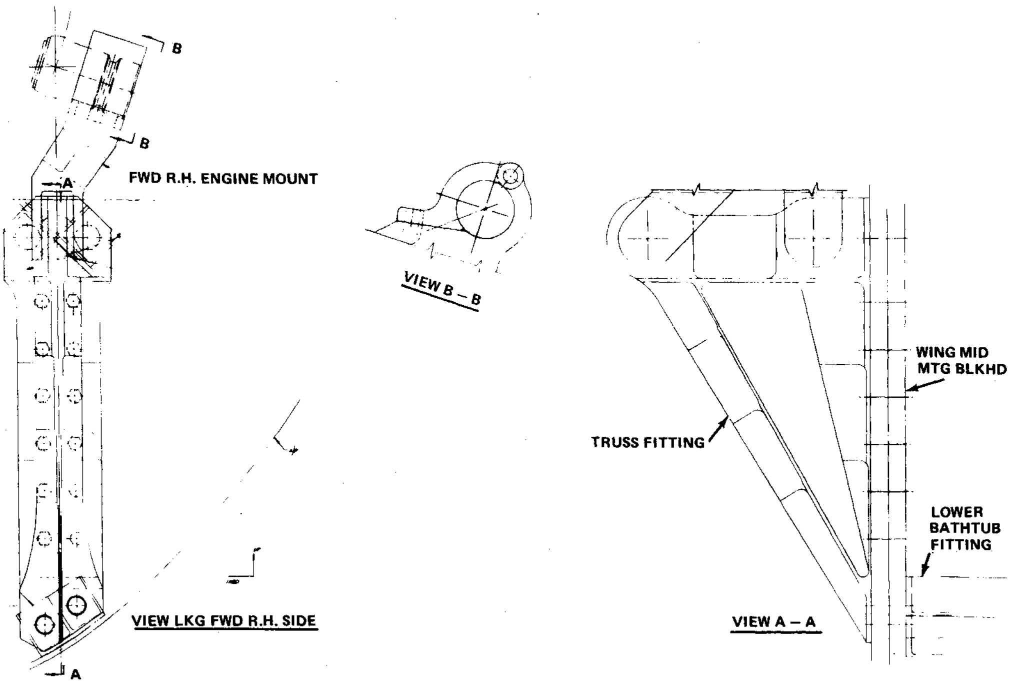

Fig. 18 Engine mount.

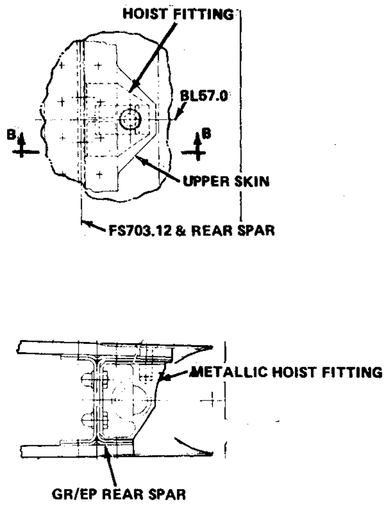

Fig. 19 Hoist fitting attachment.

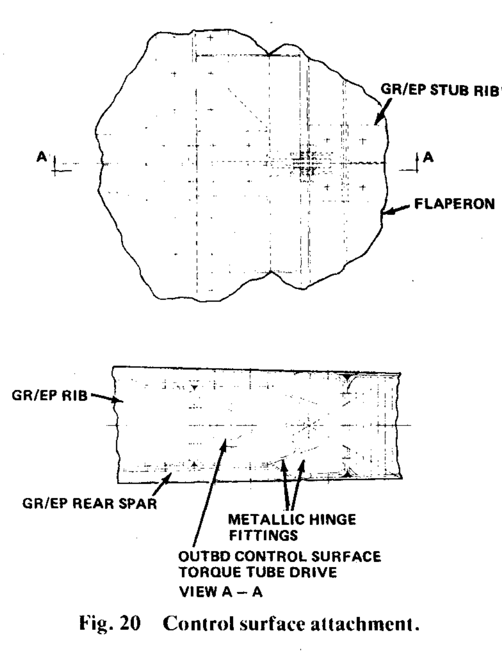

Fig. 20 Control surface attachment.

shown in Fig. 8. Being a highly swept surface, most of the bending moment is concentrated near the rear beam of the fin. The design problem is to transfer a large, highly concentrated, bending moment into a shallow ring bulkhead. Here again, an all-composite approach was initially examined, but the design became very complex and impractical. It was obvious that metallic structure should be used for the transfer of the fin cover loads to the frames. Two canted, graphite/epoxy frames at FS 742 and FS 759 are utilized. The upper portion of both frames consists of a titanium fitting bolted to the graphite/epoxy portion. The vertical fin covers, which are B/Gr/Ep hybrid locally to improve the composite net tension allowable, are bolted to splice plates integral with the titanium fitting. The fitting also doubles as a torque box, enabling the development of load in the fitting between frames in resisting the applied bending moment. Running cover loads in the this area are on the order of 14,000 lb/in. At the front spar, a shear pin oriented vertically attaches the root rib to a fitting, which in turn attaches to the FS 703 frame and reacts lateral shear. Drag shear is resisted at the main fitting.

Main Landing Gear Attachment

The main landing gear support installation is presented in Fig. 17. The landing gear trunnion is supported by a steel fitting bolted to the forward face of the bulkhead at FS 600, which also functions as the forward wing beam attachment bulkhead. Aft of the main attachment fitting, a backup fitting (landing gear drag fitting) is provided which distributes fore and aft loads into the outer fuselage side wall and the inlet duct wall. Vertical landing gear loads are transferred to bulkhead 600 by the landing gear support fitting.

Engine Mounts

The ADCA engine is supported at three locations – two forward and one aft. The left forward mount supports all three components of load, thrust, vertical, and side loads. It is a quick-connect fitting at the engine interface and rigidly attached to the FS 662.32 bulkhead. The vertical and side loads are transmitted to the side panel and structural duct by the bulkhead and the thrust load by the sloping lower pressure deck. Bathtub fittings are utilized to introduce the thrust load into the deck.

The right forward mount (Fig. 18), though having an identical interface with the engine, has the added requirement of not carrying side load. This is accomplished by utilizing

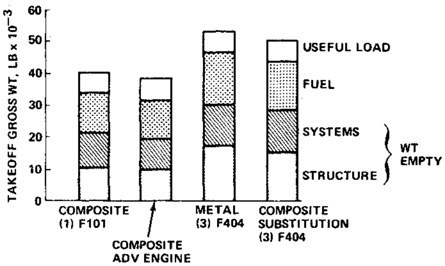

Fig. 21 Takeoff gross weight comparison.

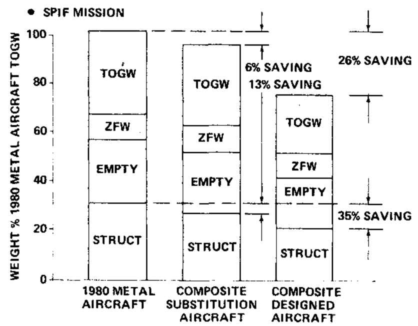

Fig. 22 Effect of composite on aircraft weights for SPIF mission.

spherical bearings in the plane of the vertical load which permits the mount to rotate about a fore and aft axis.

Hoist Fitting

The ADCA utilizes a three-point hoist system as depicted in Fig. 19. The forward hoist provision has been positioned at the centerline of the aircraft and FS 408. The two aft hoist points are placed on the wing either side of the aircraft centerline at BL 57 and FS 703. They have been positioned just aft of the wing box fuel tanks such that complex sealing requirements are avoided. In addition, the two points also serve as two of the three points required for the wing hoisting.

Control Surface Attachment

A typical control surface attachment shown in Fig. 20 depicts an inboard flaperon hinge support. Both hinge fittings – the wing side and the flaperon side – have been designed as metallic parts due to the minimum envelope into which they must fit, the magnitude of the concentrated load input, and for simplicity.

VI. Composite vs Metal Airplane Comparisons

As part of this study, 1980 advanced metal aircraft were sized to perform the same mission as ADCA. The weight reductions over current metal aircraft shown in Table 1 were used for this study. Weights of the selected ADCA are compared to weights of advanced metal and composite substitution aircraft in Fig. 21. The latter aircraft were sized for both the engines used for the ADCA screens and for "rubber" versions of these engines. The incremental weight differences between the ADCA and the advanced metal aircraft is a result of material difference plus size effects. The metal aircraft must grow in size to perform the baseline mission and it is, therefore, necessary to make large step changes in propulsion to maintain a constant level of performance. Substitution of composite for the metallic materials used in the metal aircraft, without changing vehicle size or engines, results only in a moderate weight reduction but would improve performance. This effect is shown more dramatically in Fig. 22. The composite substitution aircraft has a 13% reduction in structural weight and a 6% reduction in takeoff gross weight. In contrast, the smaller composite-designed aircraft (ADCA) has a 35% saving in structural weight and a 26% saving in takeoff gross weight. Fuel savings amount to 30% which may be very significant for aircraft operating in the 1980 time frame. In addition, a preliminary evaluation indicates that production costs of the smaller ADCA aircraft should be 25% lower than the larger advanced metal aircraft and the life cycle cost should be 21% less.

The major reasons for this cost reduction are the resizing of the vehicle made possible by the structural weight savings and the ability to reduce the number of detail parts and, therefore, reduce assembly costs as a result of the large integral structural component fabrication made possible by advanced composites technology.

VII. Conclusions

The ADCA program demonstrated that there are significant benefits to be gained by applying advanced composites in the preliminary design of new aircraft. Composite materials provide the unique capability to significantly reduce aircraft size and both procurement and life cycle costs with no sacrifice to performance.

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