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Wing Planforms for Large Military Transports

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WING PLANFORMS FOR LARGE MILITARY TRANSPORTS

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Abstract

Transport aircraft, designed for long-range military missions with heavy payloads, lead to wings with high aspect ratios and very large spans. A wing geometry/cruise speed optimization study was made of a large cantilever wing military transport airplane. Preliminary design and performance evaluations were also made of a strut-braced wing airplane. Initial results obtained with statistical weights indicated small performance advantages for the cantilever wing design. Subsequent results obtained with weights derived from detailed analytical structural analyses reversed the initial conclusions. These results indicated that unusual alternative configuration concepts cannot be discarded, based on small differences predicted during conceptual design studies.

1.0 Introduction

Increases in fuel prices and in aircraft ranges tend to favor larger wing aspect ratios, to the point where structural weight penalties offset the induced drag reductions. Projected advances in structural and materials technology have also encouraged increased wing aspect ratios during design studies of future transport aircraft. Thus, increasing fuel prices and projected military missions requiring long range, coupled with large, heavy military payloads, have lead to conceptual aircraft designs with high aspect ratio wings and very large spans.

Recently completed AFFDL/Boeing conceptual design studies[1, 2, 3, 4] of long-range (10,000 nmi) heavy payload (350,000 lb) strategic airlift aircraft have identified aspect ratios of 12 for conventional turbulent flow, and 14 for laminar flow control wings. The wing analyses were based on statistical wing weight methods that are often used during conceptual design studies. The wing designs had spans of about 400 ft. The large spans caused concerns about wing deflections, and about the substantial extrapolation of the data base as required for the wing weight analyses.

The present study[3] was initiated to quantify these concerns, since large structural deflections could ultimately limit wing span lengths, and thereby impose a strong indirect relationship between optimum wing planform characteristics and the design mission requirements of future military transports. Perhaps even more stringent limits on wing span may be set by available runway and taxiway width at land base airports.

The study was initiated by a wing geometry/cruise speed optimization of a large military transport airplane with a cantilever wing. A comparable aircraft design, having a strut-braced wing, was then developed. The strut-braced concept was evaluated by comparison with a reference cantilever wing aircraft design selected from the wing geometry/cruise speed optimization study. Both configurations were designed to identical mission requirements, using the same technology levels.

The majority of the performance and weight comparisons, and all of the economic comparisons, were based on wing weights derived from statistical weight methods. The cantilever wing and strut-braced wing designs were then reevaluated, using analytical wing structural weight analyses. Results obtained with the more detailed analytical weight estimates altered some of the initial conclusions obtained using the statistical wing weights.

The development of the cantilever wing configuration, including results of the wing geometry/cruise speed optimization study, are discussed in Section 2.0. The strut-braced wing configuration is described in Section 3.0. Section 4.0 contains descriptions of the detailed structural analyses of the very large-span wings. Weight and performance comparisions of the strut-braced and cantilever wings are presented in Section 5.0. Section 6.0 contains the study conclusions.

2.0 Cantilever Wing Configuration

Design mission objectives for the study configurations included a 10,000-nmi range, a 350,000-lb payload, and a military takeoff field length limit of 9,000 ft.

The design range of 10,000 nmi represents an environment where fuel is not available en route to, or on arrival at, a Mideast deployment point. The payload and cargo-box size were determined by the desire to transport approximate weight multiples of main battle tanks, and military outsize cargo requirements. The military takeoff field length was set at 9,000 ft. to permit use of a majority of available terminals with conventional runways. Additional requirements were: ability to carry cargo pallets or containers, drive-through capability, and a pressurized cargo compartment.

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The reference cantilever wing configuration shown in Figure 1 was developed from configurations of previous studies[2, 4] that met these design mission objectives. The technology level assumed a start of prototype production in 1985, first flight about 1989, and an initial operational capability after 1990. Selection of the three-bay fuselage was dictated by the design payload requirements of either three main battle tanks (high-density loading), or 75 military pallets (low-density loading). The high wing and kneeling landing gear permit a cargo floor loading height of 84 in. The wing planform was selected for efficient long-range cruise performance, incorporating the benefits of active controls and advanced composites structural materials. The canted "π" tail empennage arrangement is a structurally efficient design that provides drive-through and air-drop capability, while the use of active controls, together with the double-hinged rudder, results in minimum tail areas. The propulsion system consists of four 1985-technology high bypass ratio engines located on the wing, primarily because of airplane balance requirements. Spanwise locations were set by flutter considerations, and provide wing bending relief.

The preliminary design selection chart for this airplane, Figure 2, parametrically shows the effect of thrust/weight ratio (T/W) and wing loading (W/S) on airplane gross weight and block fuel requirements for an otherwise fixed configuration. Performance factors and constraints, such as takeoff field length (TOFL), initial cruise altitude capability (ICAC), and the ratio of the initial cruise lift coefficient capability to the lift coefficient for maximum lift/drag ratio (C_{L_R}) also are identified. The minimum gross weight airplane required

a high wing loading of approximately 140 lb/ft^2 and could not meet the TOFL requirement. The minimum fuel burned airplane required a lower wing loading (110 lb/ft^2), and also did not meet the TOFL requirement of 9,000 ft. The design was selected by considering the trade between fuel burned, and gross weight along the TOFL = 9,000 ft constraint line.[3] The selected design, which had a wing loading of 108 lb/ft^2, achieved nearly the minimum fuel and minimum gross weight possible for this configuration.

The preceding design provided a baseline configuration to begin the wing geometry/cruise speed optimization study. The technique used[5] consisted of the five sequential steps in Figure 3. Values of the primary wing variables; i.e., thickness ratio (t/c), aspect ratio (AR), and quarter chord sweep $\Lambda c/4$ are defined in step I. Since four values were specified for each of the three variables, there are 64 possible combinations. In step II, the method of orthogonal Latin squares was used to define the minimum number of wing designs (16) that accurately represented the entire matrix of study configurations. In step III, each of the 16 selected designs was evaluated by the engine/airframe matching technique used to obtain Figure 2.

The 16 selected designs were all close to the TOFL-constrained minimum fuel configuration, and also to the constrained minimum gross weight configurations.[3] The corresponding wing loadings varied from 85 to 110 lb/ft^2. Values for the principal design figures of merit; i.e., fuel burned, takeoff gross weight, and productivity, were calculated. This process also provided values of the secondary
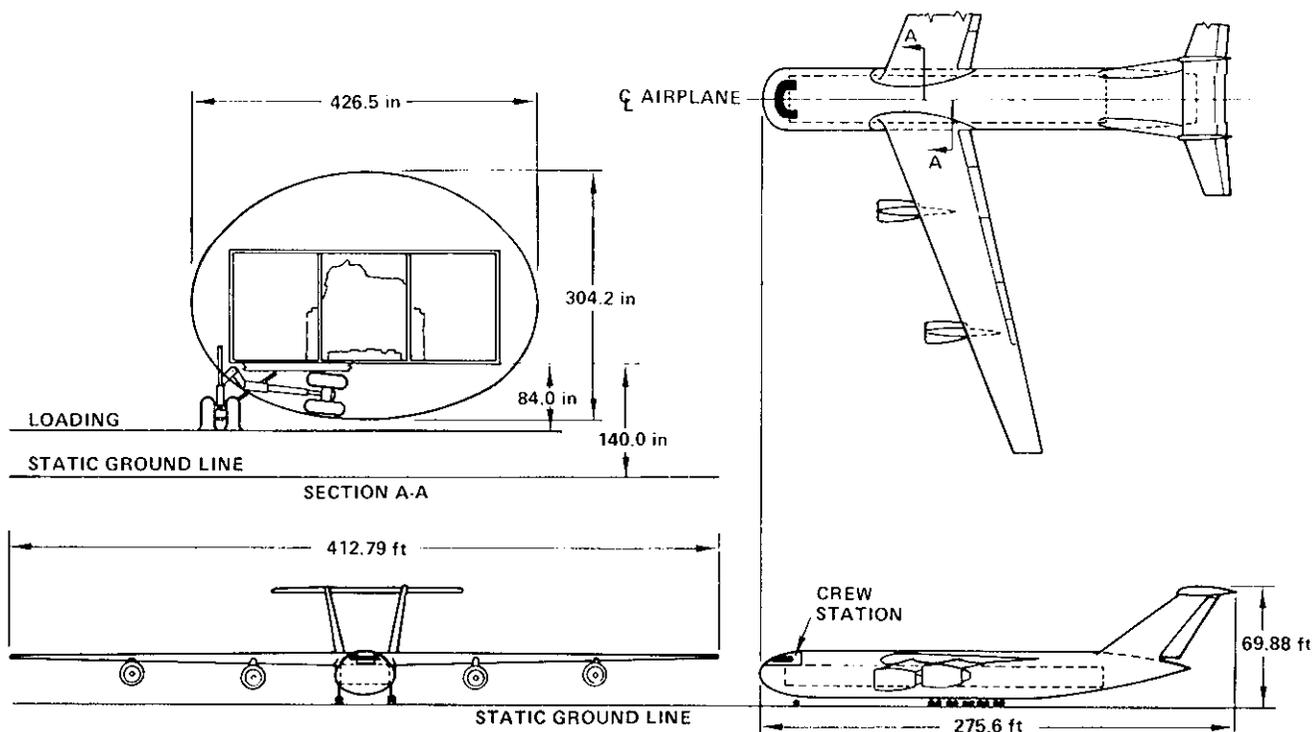

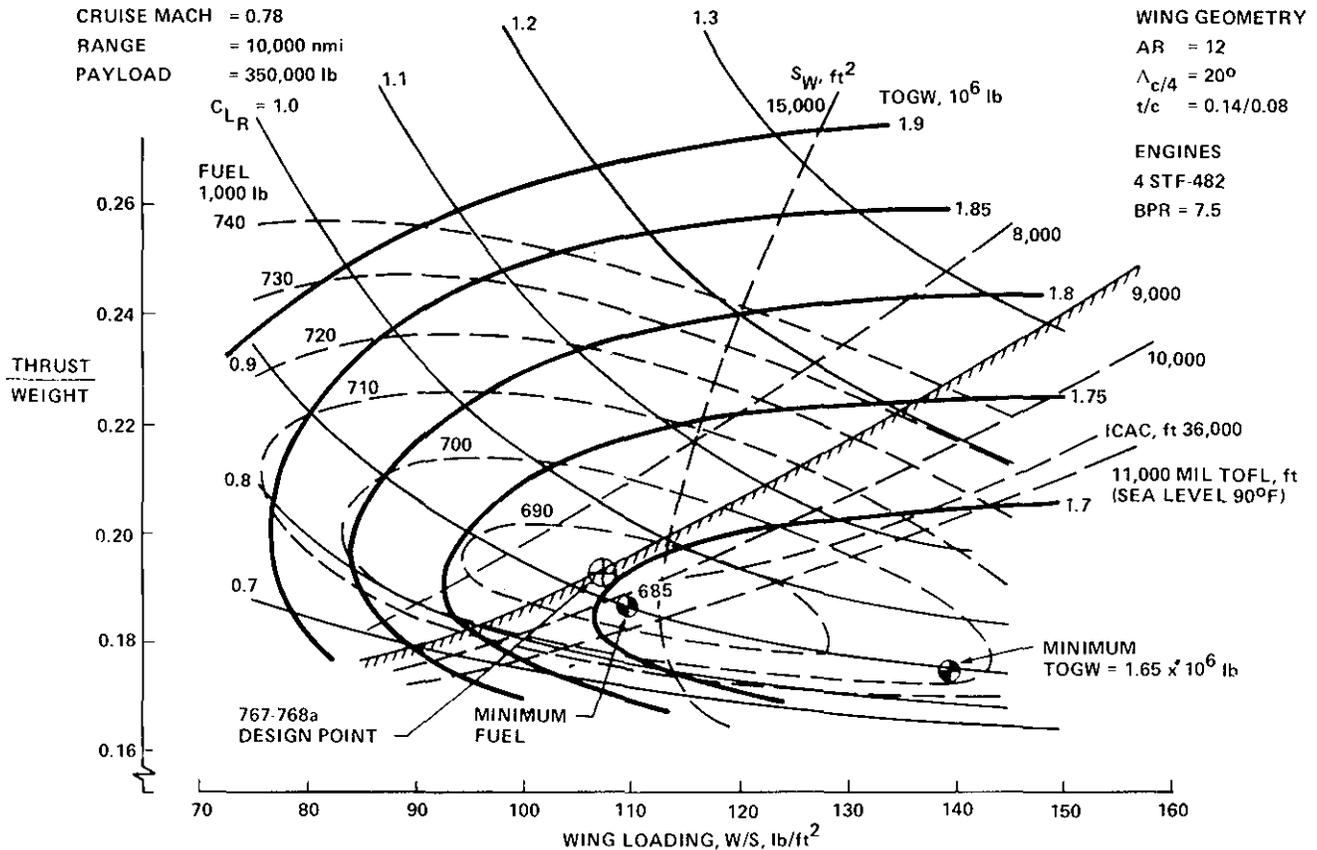*Figure 1   Cantilever Wing Configuration*

CRUISE MACH = 0.78
RANGE = 10,000 nmi
PAYLOAD = 350,000 lb

WING GEOMETRY
AR = 12
$\Lambda_{c/4}$ = 20°
t/c = 0.14/0.08

ENGINES
4 STF-482
BPR = 7.5

C_{L_R} = 1.0
1.1
1.2
1.3

S_W, ft²
15,000

TOGW, 10^6 lb
1.9
1.85
1.8
1.75
1.7

FUEL
1,000 lb
740
730
720
710
700
690
685

8,000
9,000
10,000

ICAC, ft 36,000

11,000 MIL TOFL, ft
(SEA LEVEL 90°F)

0.9
0.8
0.7

$\frac{THRUST}{WEIGHT}$

0.26
0.24
0.22
0.20
0.18
0.16

MINIMUM
TOGW = 1.65 x 10^6 lb

767-768a
DESIGN POINT

MINIMUM
FUEL

70 80 90 100 110 120 130 140 150 160

WING LOADING, W/S, lb/ft²

Figure 2   Cantilever Wing Airplane Engine/Airframe Matching

I	II	III	IV	V
STUDY VARIABLE DEFINITION	DESIGN SELECTION [ORTHOGONAL LATIN SQUARES]	EVALUATIONS OF SELECTED DESIGNS	REGRESSION ANALYSIS APPROXIMATING FUNCTIONS	SYSTEM OPTIMIZER

• PRIMARY VARIABLES

WING: t/c = 0.08 → 0.14

AR = 8 → 14

$\Lambda_{c/4}$ = 10 → 30°

• SECONDARY VARIABLES

SIZE: W/S
T/W

CRUISE: MACH
ALTITUDE

• CONSTRAINTS
  • RANGE
  • PAYLOAD
  • TOFL

• FIGURES OF MERIT
  • FUEL
  • TOGW
  • $\frac{MPL}{TOGW}$

$\Lambda_{c/4}$ AR = 8
30 25 20 10
.08 .10 .12 .14
t/c

$\Lambda_{c/4}$ AR = 10
30 25 20 10
.08 .10 .12 .14
t/c

$\Lambda_{c/4}$ AR = 12
30 25 20 10
.08 .10 .12 .14
t/c

$\Lambda_{c/4}$ AR = 14
30 25 20 10
.08 .10 .12 .14
t/c

• POSSIBLE DESIGNS
X SELECTED DESIGNS
⊕ BASELINE AIRPLANE

• CONFIGURATION DEFINITION
• EVALUATION AND SCALARS
  • AERODYNAMICS
  • WEIGHTS
  • FLIGHT CONTROLS
• CRUISE MACH OPTIMIZATION

DESIGN OPTIMIZATION

T/W

W/S

OPTIMIZED DESIGN
• GEOMETRY
• FUEL
• TOGW
• TOFL
• ALTITUDE

REPEAT FOR EACH DESIGN

• TOGW = f^N (t/c, AR, Λ)
• FUEL = f^N (t/c, AR, Λ)
• TOFL = f^N (t/c, AR, Λ)
• OEW = f^N (t/c, AR, Λ)
• M_{OPT} = f^N (t/c, AR, Λ)
• h_{OPT} = f^N (t/c, AR, Λ)

• OPTIMIZATION
• CONSTRAINED OPTIMIZATION
• SENSITIVITIES
• TRADES
• POINT DESIGN DEFINITION

INCREASING t/c
MACH

INCREASING SWEEP
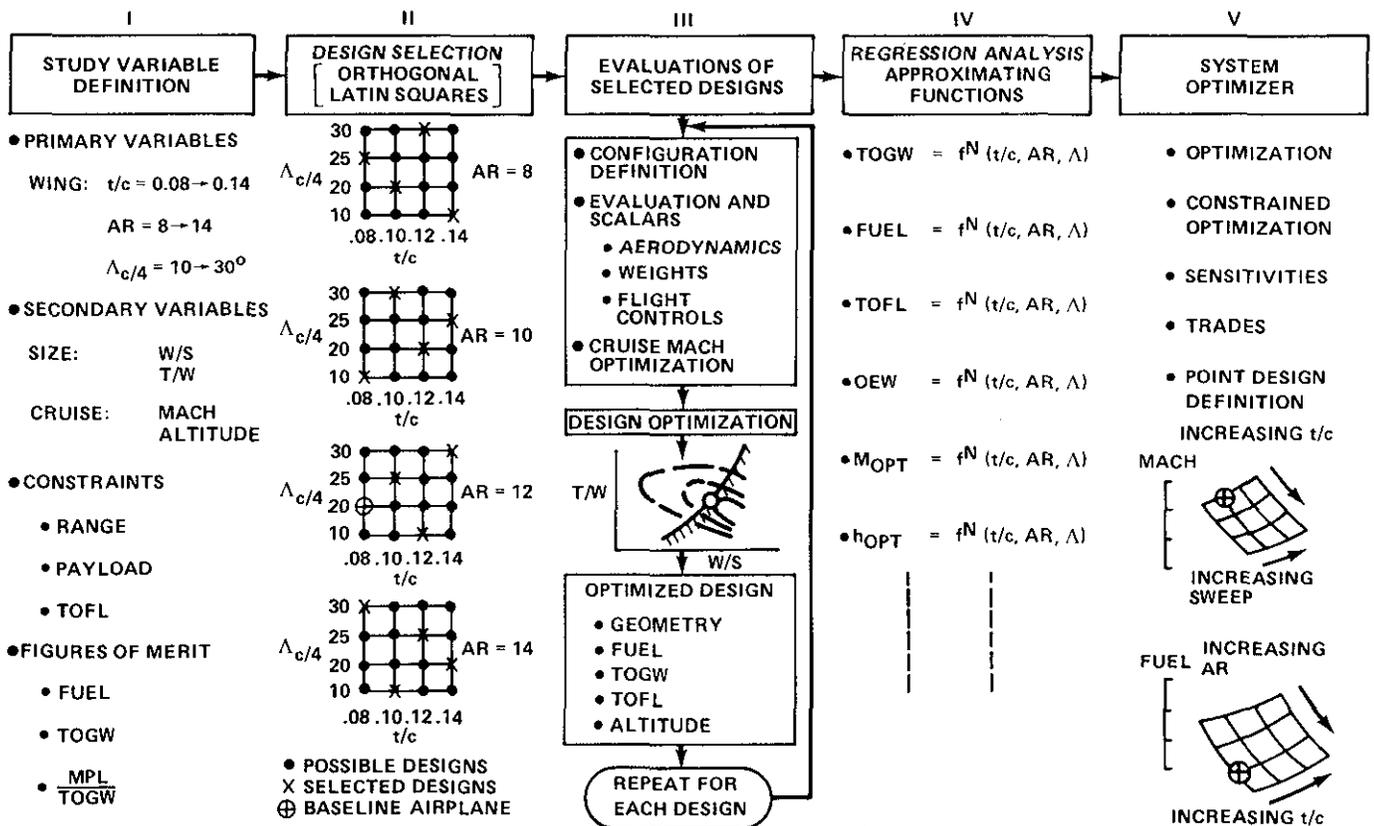
FUEL INCREASING AR

INCREASING t/c

Figure 3   Wing Parametric Optimization Study

3

variables; i.e., wing loading, thrust-to-weight ratio, Mach number (M), and cruise altitude, that satisfy the design constraints.

A forward step regression analysis method was used in step IV to construct approximating functions to represent the relationship between the dependent and the independent variables. The dependent variables included the secondary variables and the principal design figures of merit.

Step V used a powerful nonlinear optimizer on the constructed approximating functions to conduct constrained or unconstrained optimization studies, sensitivity studies, and trade studies.

Results of the wing geometry/cruise speed optimization study illustrate the impact of wing planform geometry on the cruise Mach number (Figure 4), block fuel (Figure 5), TOGW (Figure 6), and productivity (Figure 7). The surface fit equations from the regression analysis are a good representation of the preliminary baseline configuration and the additional 15 configurations. The wing geometry (primary variables) and cruise Mach number for the resulting minimum fuel, minimum TOGW, and maximum productivity airplanes are shown in Table 1. Sensitivities of the airplanes to changes in the wing planform are also shown. Sensitivity is defined to be the change in the primary figure of merit; i.e., fuel burned, that occurs over the entire range of values for the particular design variable.

The optimum planform for the minimum fuel airplane has the highest aspect ratio and the lowest sweep and thick-ness/chord ratio. This combination results in a cruise Mach number of 0.76. The sensitivity data show that a high aspect ratio and low thickness/chord ratio are the most important items for minimum fuel (largest sensitivity coefficients in Table 1), and sweep is of lesser importance.

The minimum fuel consumption configuration is also the minimum gross weight configuration for these payload and mission requirements. However, a comparison of Figure 6 with Figure 5 shows that, for the minimum TOGW airplane, the optimum wing aspect ratio decreases as either wing thickness or sweep increases, whereas it does not for the minimum fuel airplane. The sensitivity data in Table 1 show that gross weight varies by approximately 10% for changes in either aspect ratio, thickness/chord ratio, or wing sweep over the range of values considered. Figure 6 shows that the wing aspect ratio could be reduced from 14 to 12, with a minor penalty in gross weight at the lower, optimum thickness/chord ratios.

The maximum productivity configuration has a low thick-ness/chord ratio and an aspect ratio of 12.7. The large sensitivity coefficient in Table 1 shows that low thickness/chord ratio is most important in achieving high productivity. Wing sweep did not significantly affect productivity, because the gross weight variations with sweep were proportional to the Mach number changes.

Results of the wing geometry/cruise speed optimization showed that a wing planform with aspect ratio of 14, thickness ratio variation of 0.14/0.08 (inboard/outboard), and sweep of 10 deg minimizes gross weight and fuel consumption. This condition was nearly the maximum productivity configuration.
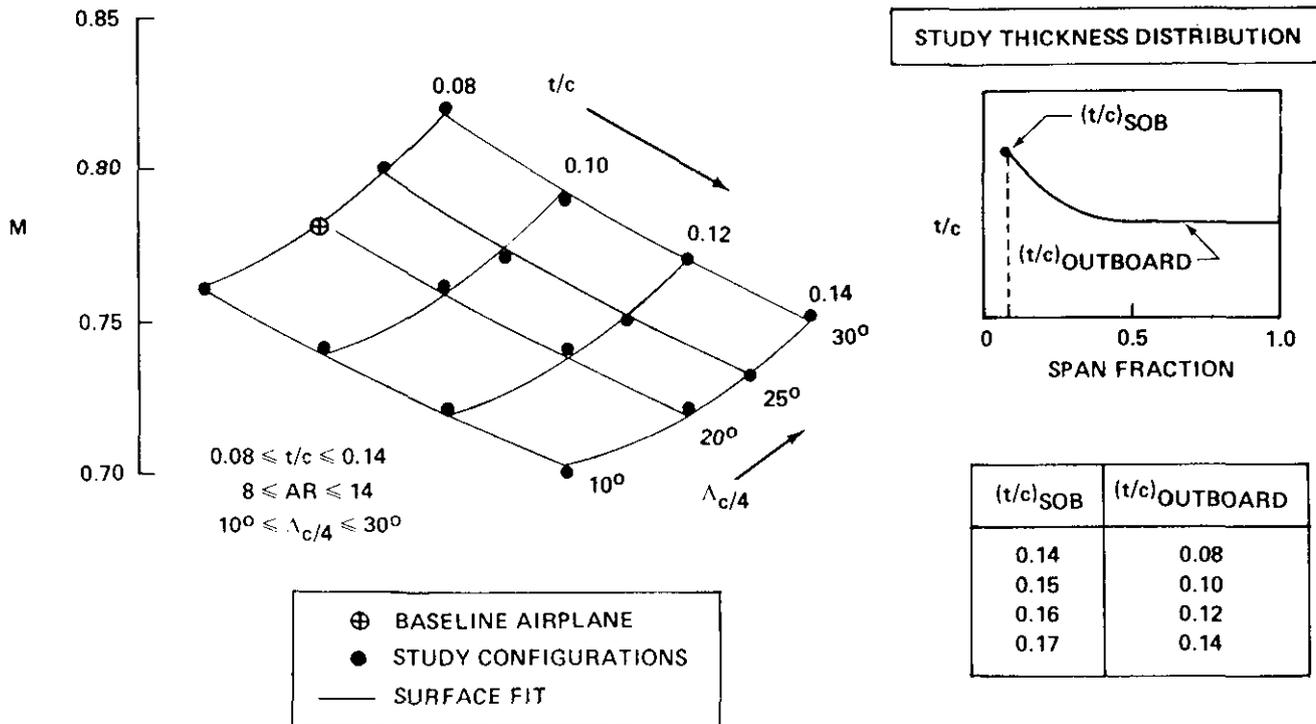

STUDY THICKNESS DISTRIBUTION

(t/c)$_{SOB}$	(t/c)$_{OUTBOARD}$
0.14	0.08
0.15	0.10
0.16	0.12
0.17	0.14

⊕ BASELINE AIRPLANE
● STUDY CONFIGURATIONS
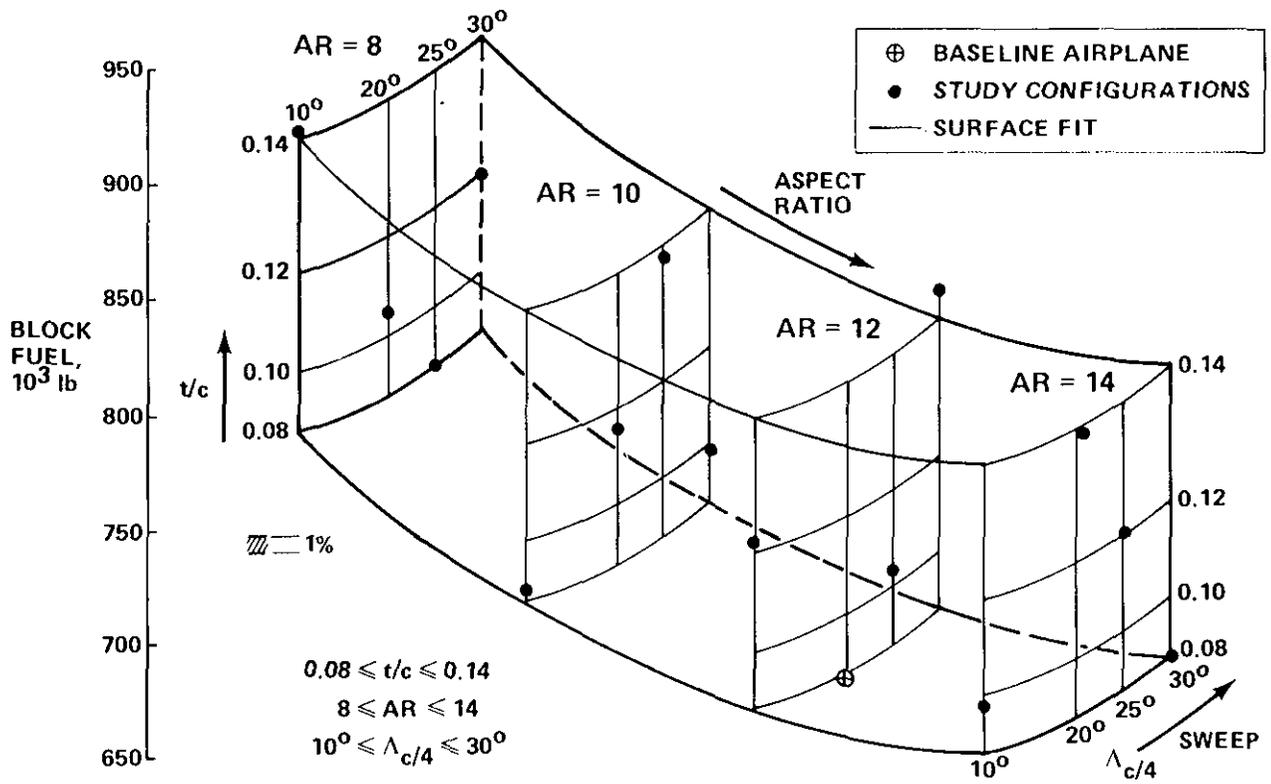—— SURFACE FIT

Figure 4   Cruise Mach Number
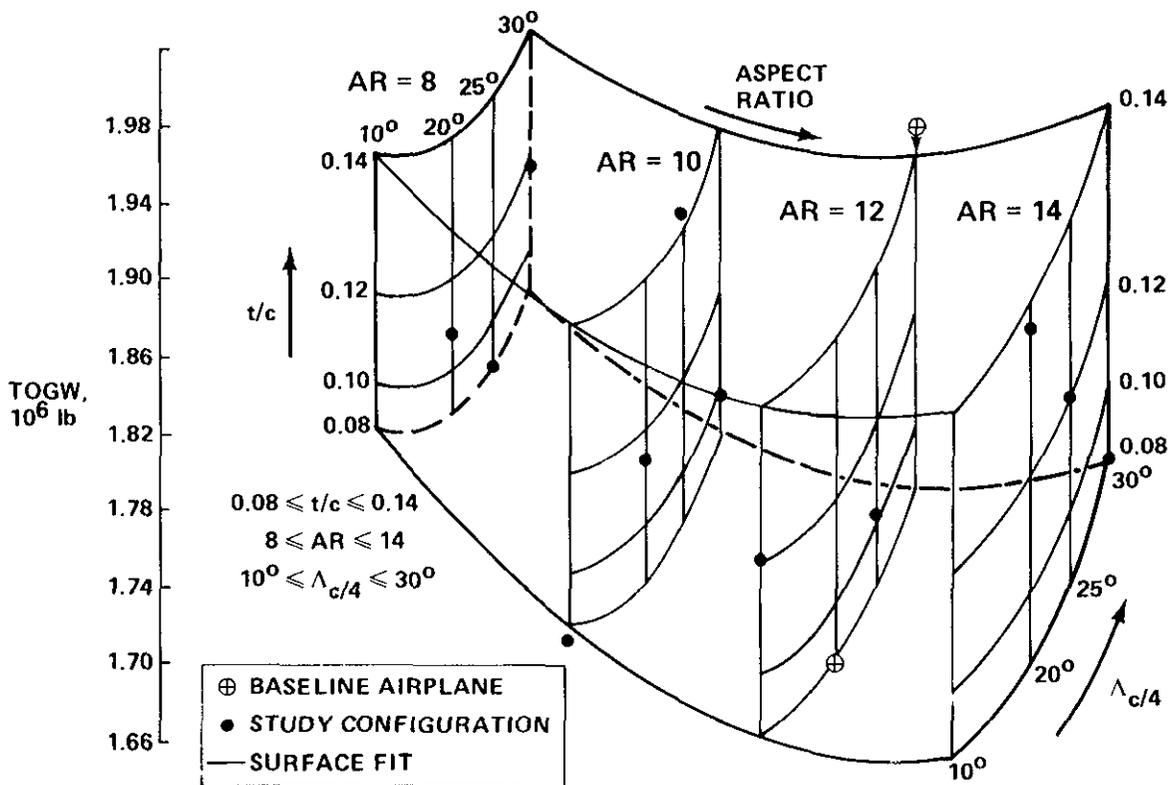
4

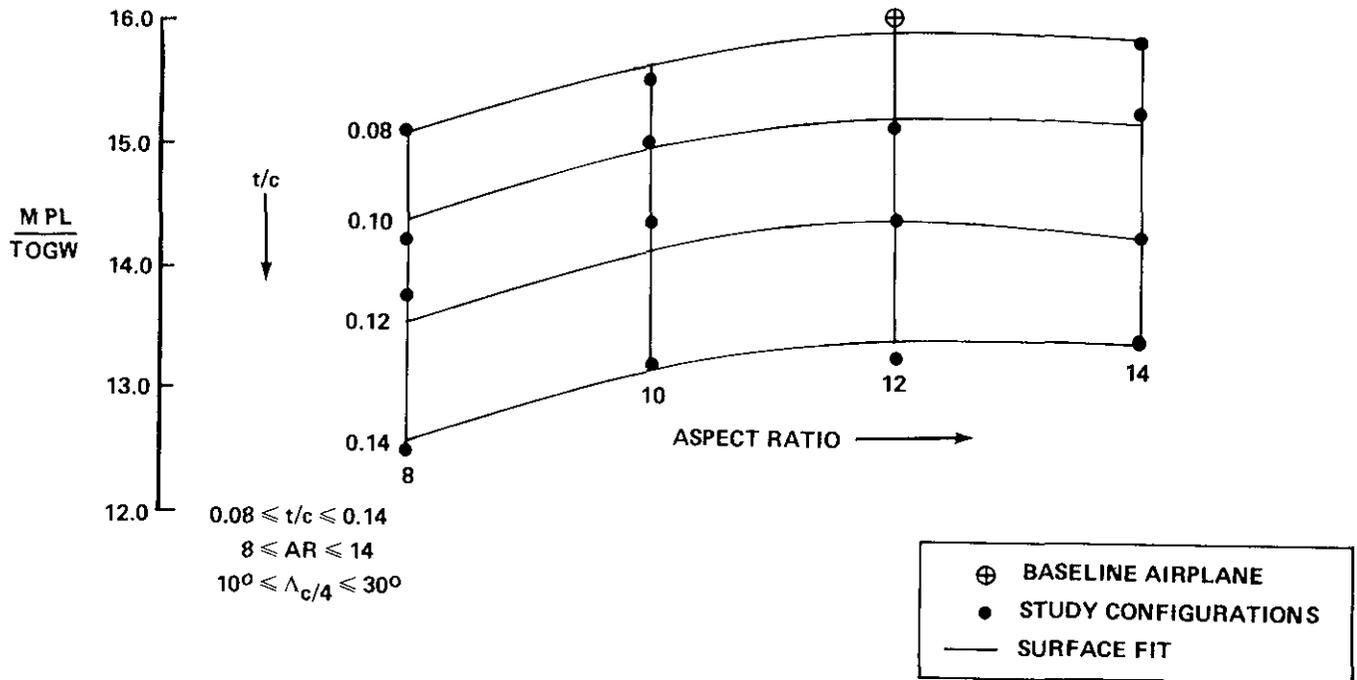*Figure 5   Block Fuel*

Figure 6   Takeoff Gross Weight

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Figure 7 Productivity (MPL/TOGW)

Table 1 Optimum Configuration and Design Sensitivities

CONFIGURATION	PRIMARY FIGURE OF MERIT:	CHANGE (%)	DESIGN VARIABLE RANGE	OPTIMUM
Minimum fuel A/P M = 0.76	Fuel:	21.4	AR = 8 → 14	14
		19.6	t/c = 0.08 → 0.14	0.08
		6.7	$\Lambda_{c/4}$ = 10° → 30°	10°
Minimum TOGW A/P M = 0.76	TOGW:	10.4	AR = 8 → 14	14
		9.8	t/c = 0.08 → 0.14	0.08
		9.6	$\Lambda_{c/4}$ = 10° → 30°	10°
Maximum $\dfrac{MPL}{TOGW}$ A/P	$\dfrac{MPL}{TOGW}$:	−5.2	AR = 8 → 14	12.7
		−15.7	t/c = 0.08 → 0.14	0.08
		Not significant	$\Lambda_{c/4}$ = 10° → 30°	Not Significant

The wing sweep, however, could be increased to 20 deg and the aspect ratio could be reduced to 12 without significantly affecting fuel consumption, gross weight, or productivity. These changes result in an increase in cruise speed from Mach 0.76 to Mach 0.78. Additionally, the wingspan would also be reduced and this is structurally desirable to reduce wing tip deflections. Consequently, a near-optimum cantilever wing was selected. This wing has the following characteristics: aspect ratio 12, quarter chord sweep 20 deg, thickness/chord ratio 0.14 inboard/0.08 outboard, and cruise Mach number 0.78.

The development of the strut-braced wing configuration is described in Section 3.0.

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3.0 Strut-Braced Wing Configuration

Strut-braced wings offer the possibility of structurally efficient large-span wings. This possibility is particularly true when advanced composites structural materials are used. The possibility of a more efficient large-span wing provided the motivation to reassess the merits of strut-braced wings.

There has been considerable research on various strut arrangements, including multiple jury struts, by W. Pfenninger[6] in connection with both laminar flow control and turbulent airplane design. Wind tunnel tests in 1957 showed that the isolated wing lower surface pressure distribution could be maintained in the presence of a strut, if the wing under-surface were cut out by less than half the strut thickness. Recent Boeing wind tunnel results[3] indicate that unfavorable aerodynamic interference between wing and strut can also be minimized by proper tailoring of the wing and/or strut, particularly near the wing/strut intersection. Large decreases in strut drag, and increased drag divergence Mach number, were evident when a wing with a tailored, cambered strut was compared to a wing with a symmetrical strut. Additional detailed aerodynamic design and test verifications are necessary to identify minimum strut effects on profile and compressibility drag. However, an interference factor of 10% was applied to the strut-isolated profile drag, and a critical Mach decrement of 0.01 was used to account for strut interference effects in the study reported herein.

The strut-braced airplane was derived from the cantilever airplane by modifying the wing planform to accommodate the strut, and resizing the aircraft to achieve identical mission performance. Recent Boeing strut-braced wing studies, such as shown in Figure 8, were used to define the strut-braced wing configuration, and to reduce the large number of design variables that must be examined to optimize a strut-braced wing. Design guidelines used to develop the strut-braced wing configuration included: strut/wing attachment angle 12 deg, strut thickness/chord ratio 10%, wing planforms outboard of the strut attachment geometrically similar to the reference cantilever wing, constant wing chord inboard of strut attachment, and strut and wing quarter-chord sweep equal to 20 deg. The strut attaches to the fuselage ahead of the foremost main landing gear and the leading edge of the strut falls behind the leading-edge flaps at the outboard attachment station. This configuration resulted in a strut chord equal to one-half the wing chord.

The shortened, constant-inboard wing chords reduced the wing area, and consequently increased the aspect ratio from 12 to 13.5. The wing thickness/chord definition was the same as on the cantilever wing (14% inboard, 8% outboard). However, the braced wing was thinner inboard, due to the reduced wing chords. The braced wing was "sheared-up" inboard equal to half the reduction in wing thickness, so that the top of the wing matched that of the reference configuration at the wing/body junction. This arrangement provided the greatest wing/strut spacing at the body, without changing the fuselage design. The combination of strut attachment angle and side-of-body wing/strut spacing resulted in a strut attachment at approximately 45% wing semispan. The inboard engine was located at the strut attachment station to provide a wing/strut separation distance of 20 in., and the outboard engine location was unchanged relative to the cantilever wing location. The leading-edge and trailing-edge flaps, spoilers, etc., were constant length inboard of the strut attachment station.
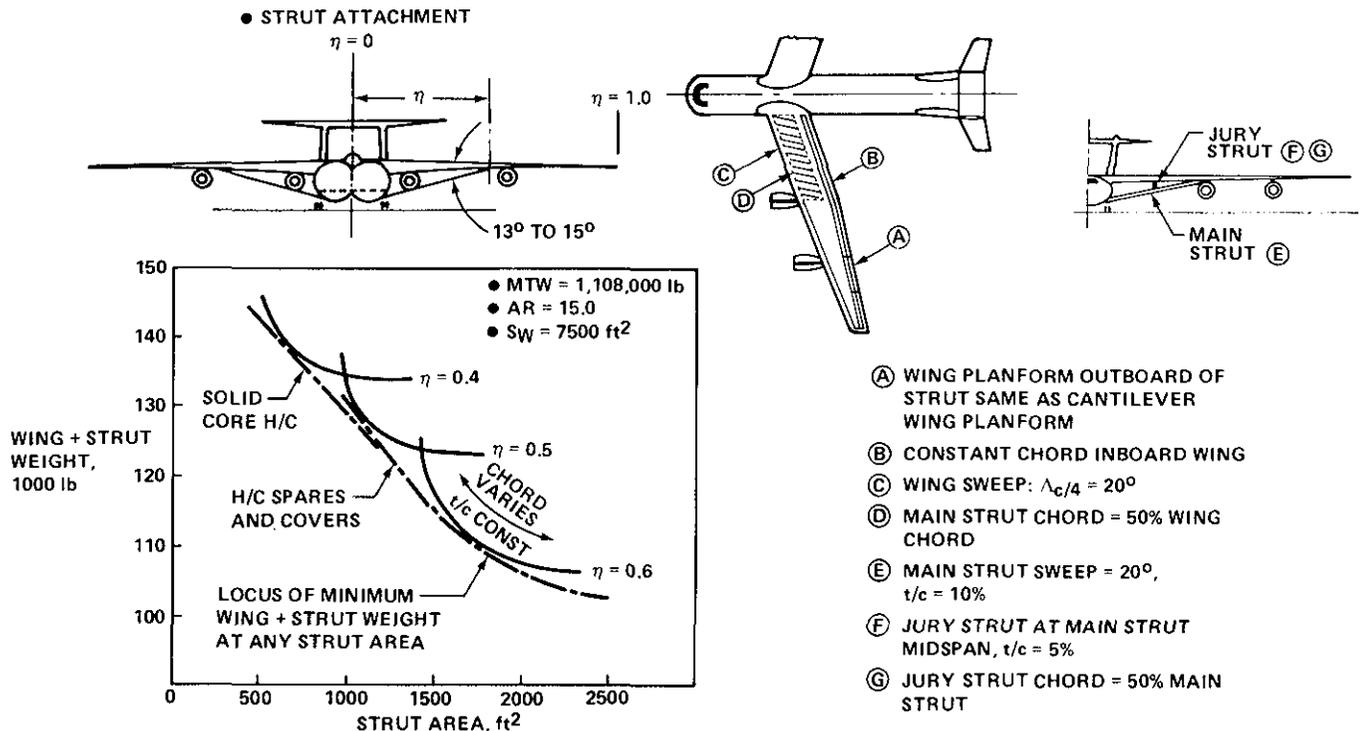

● STRUT ATTACHMENT

● MTW = 1,108,000 lb
● AR = 15.0
● S_W = 7500 ft^2

(A) WING PLANFORM OUTBOARD OF STRUT SAME AS CANTILEVER WING PLANFORM

(B) CONSTANT CHORD INBOARD WING

(C) WING SWEEP: $\Lambda_{c/4}$ = 20°

(D) MAIN STRUT CHORD = 50% WING CHORD

(E) MAIN STRUT SWEEP = 20°, t/c = 10%

(F) JURY STRUT AT MAIN STRUT MIDSPAN, t/c = 5%

(G) JURY STRUT CHORD = 50% MAIN STRUT

Figure 8   Strut-Braced Wing Design Considerations

Preliminary structural analyses of the strut-braced wing indicated the desirability of a jury strut. Consequently, the final strut-braced wing definition included a 5%-thick jury strut located at midspan of the main strut with chord one-half that of the main strut chord. The general arrangement of the strut-braced wing configuration is shown in Figure 9.

The design selection chart for this configuration is shown in Figure 10. The minimum gross weight configuration would require a wing loading of 140 lb/ft^2, while the design wing loading for minimum fuel was less than 110 lb/ft^2. Neither configuration met the TOFL requirement. The final design selection for the strut-braced wing configuration had a wing loading of 120 lb/ft^2. It is the TOFL-constrained minimum TOGW configuration, and achieves nearly the minimum fuel requirements.[3]

4.0 Wing Structural Analyses

The preceding cantilever and strut-braced wing airplanes were sized and optimized, using weights calculated by statistical weights estimation techniques. The degree of data extrapolation necessary for these weight calculations was minimized by scaling from analytical wing weights derived in previous Boeing large freighter studies. The weight and performance comparisons of the strut-braced wing and the cantilever wing configurations are presented in Section 5.0. This discussion follows the detailed analytical structural weight analyses described in Section 4.0.

Detailed structural analyses were made of the cantilever wing (with inboard/outboard thickness/chord ratios of 0.14/0.08, 0.15/0.10, and 0.16/0.12) and the strut-braced wing, to provide analytical wing weights and an understanding of the elastic characteristics of very large-span wings. Flutter evaluations were not included. Although large deflections were anticipated, the wings were strength-sized, and the wing deflections were noted for comparative evaluations.

The basic structural material is 350 cure T300 graphite/epoxy, assumed to be 1985 technology-available for in-service in the mid-1990 time period. Material requirements for the cantilever wings were determined by using a computerized wing structural synthesis program, ORACLE, that combined an aerodynamic loads analysis, a simplified box-beam stress analysis, and a weight analysis of the wing box. A flow chart for ORACLE is shown in Figure 11. The aeroelastic loads analysis is based on beam theory and lifting-line aerodynamics.[7]

The elastic properties of the wings were described by bending stiffness, EI, and torsional stiffness, GJ. The box-beam stress analysis included the effect of combined shear and axial stress. The structural analyses provided definition of the wing material requirements necessary for the analytical weight evaluations of the cantilever and strut-braced wing planforms. These theoretical evaluations of the wing primary structure, plus statistical evaluations of the secondary structural weight items, comprised the analytical weight evaluations of the large-span wings. The weight analysis procedure is described in Reference 8.
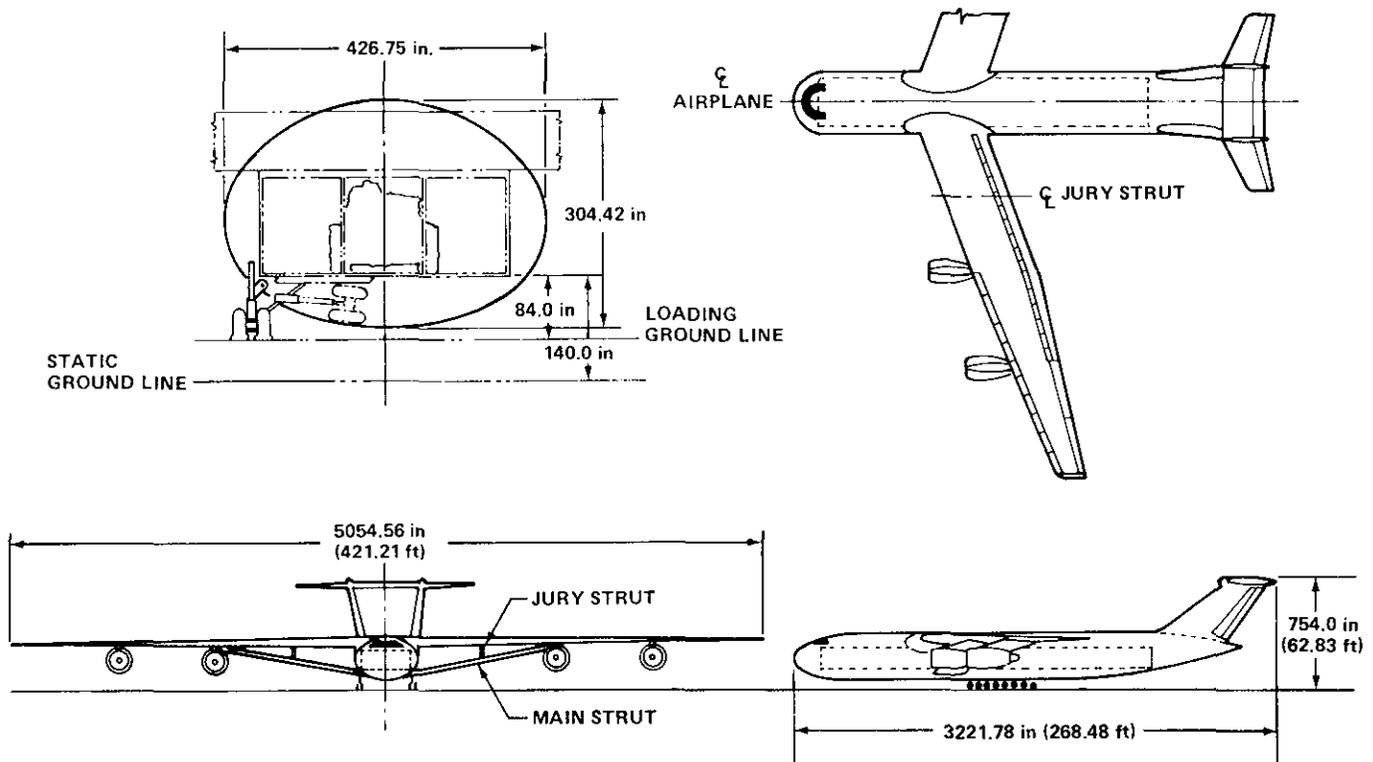

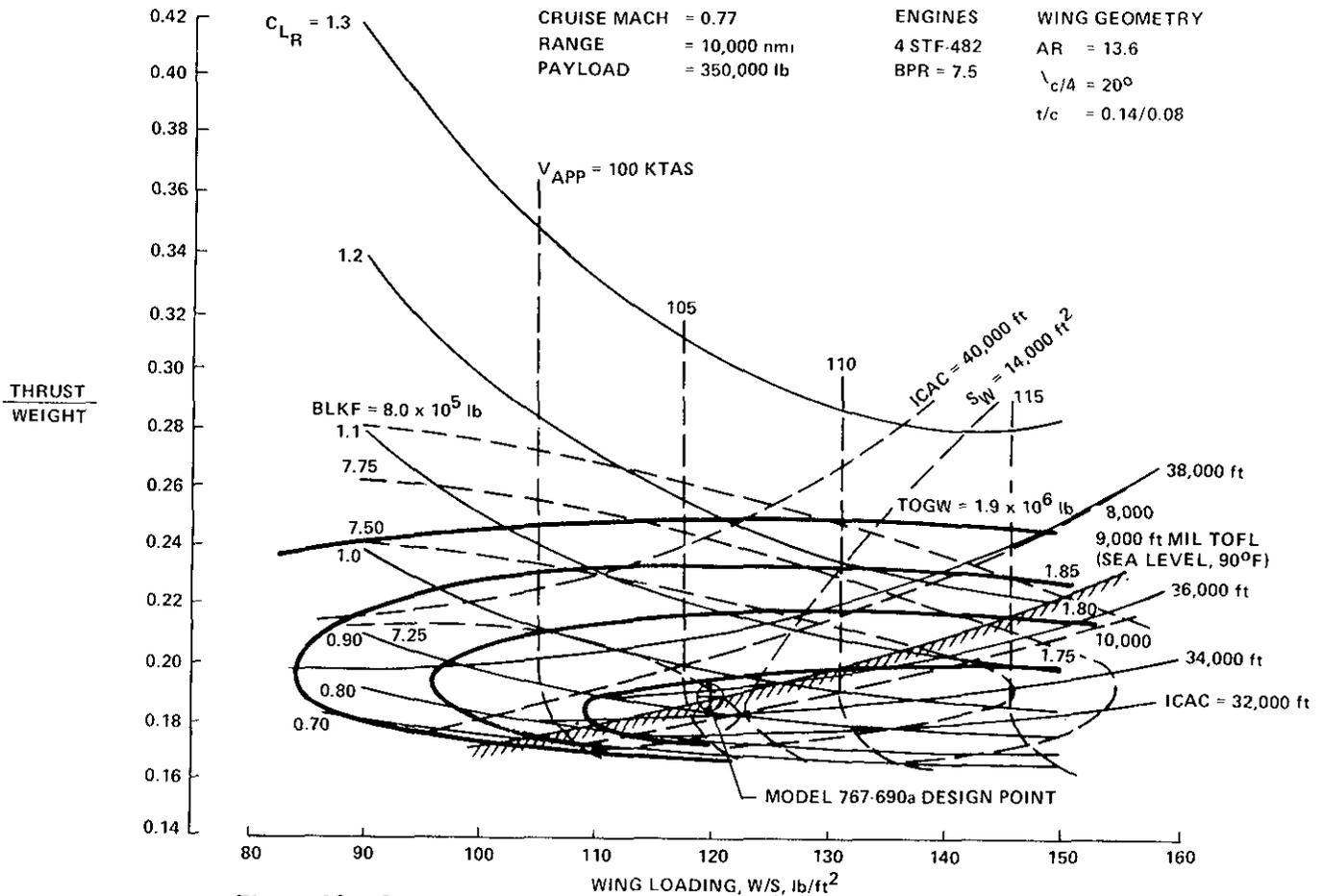Figure 9   Strut-Braced Wing Configuration, Model 767-790

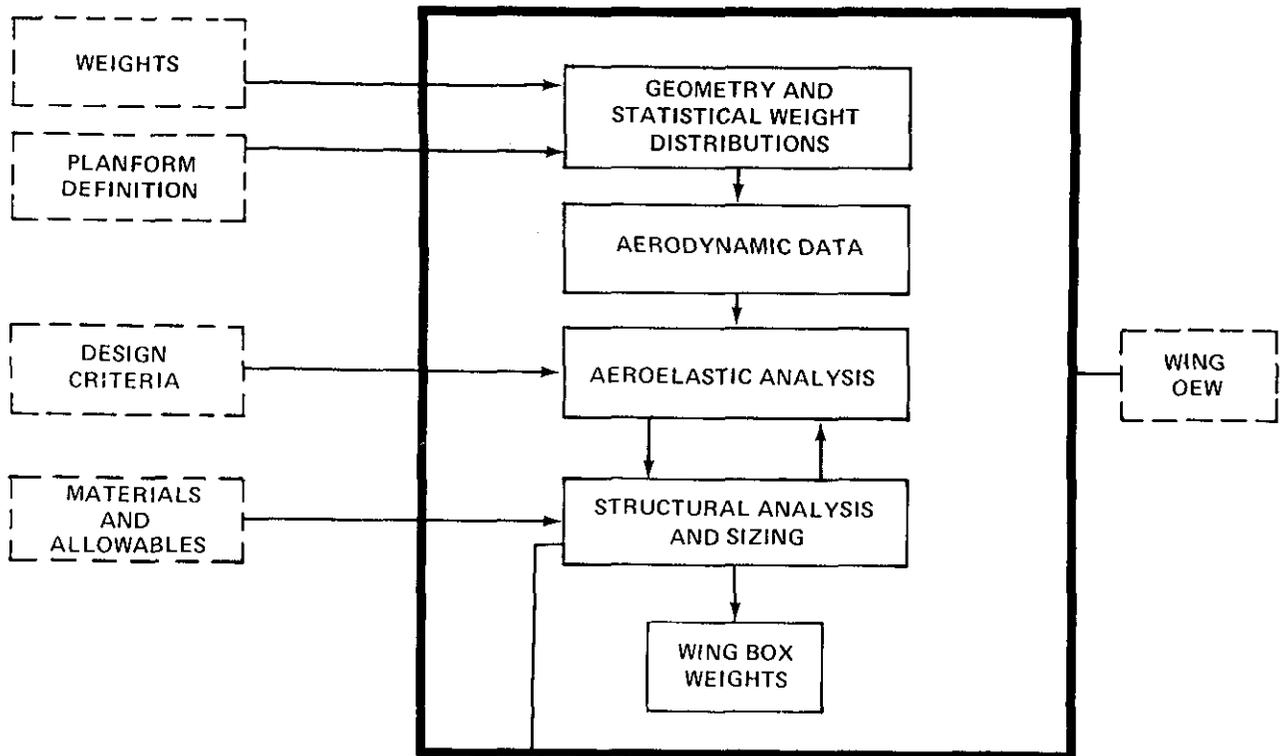Figure 10   *Strut-Braced Wing Airplane Engine/Airframe Matching*

Figure 11   *ORACLE—Structural Synthesis Program*

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The locations of spars and the load reference axis used for all of the cantilever wings are shown in planview in Figure 12. All of the wings were sized by the 2.5g maneuver condition and the 1.67g taxi condition. The differences in wing thickness distributions of the three cantilever wings had little effect on the design loads, shown for the thinnest wing in Figure 12.

The effects of active controls have been estimated and included in the wing load calculations. Gust load alleviation was estimated to produce a 15% reduction in the incremental gust load factor, and was simulated by an appropriate reduction in dynamic gust factor. Maneuver load alleviation (MLA) was investigated by deflecting either an outboard aileron (Figure 12) with the trailing edge up, or an inboard flap with the trailing edge down, to shift wing lift loading inboard and thereby reduce the wing root bending moment. When the ailerons were deflected, the flexible wings tended to wash in at the tips, thereby shifting the wing lift outboard. Hence, use of the ailerons actually produced an undesirable increase in root bending moment. When the inboard flaps were deflected, the lift loading shifted inboard, producing a desired reduction in root bending moment. Hence, an MLA system using the inboard flaps provided a wing weight saving for the study configurations.

Results of the wing weight evaluations, based on structural analyses, are shown in Figure 13 as weights relative to the statistical weight evaluations of the reference cantilever wing (t/c = 0.14/0.08). The statistical weight analyses underpredicted the wing weights, particularly for the thinner wings.

The effects of wing thickness on wing weight as predicted by the analytical and the statistical methods are, however, similar.

The strut-braced wing has been structurally analyzed by iterative procedure shown in Figure 14. Initially, an equivalent stiffness was assumed for the portion of the wing supported by the main strut/jury strut arrangement. The beam analysis program, ORACLE, was then used to calculate the aeroelastic loads and deflections of the "equivalent" cantilever wing representation of the strut-braced wing. The initial aeroelastic loads and estimated stiffness were then imposed on a finite element model of the wing and strut geometry. The finite element model provided the distribution of the loads between the strut and wing, and the corresponding internal loads. The inboard wing and strut were resized, based on the internal loads from the finite element program, and new stiffnesses were incorporated into the modeling of the wing. Iteration was concluded when the wing and strut loads, deflections, and stiffnesses sufficiently converged.

The strut-braced wing spar locations and design loads are shown in Figure 15. Note that, by comparison with Figure 12, the shear load has a reduced maximum value and reverses direction inboard of the strut, the maximum bending moment is reduced by one-half, and the peaks in torsion at the side-of-body juncture have been removed.

Vertical deflections of the cantilever wings and the strut-braced wings are shown in Figure 16 at taxi, cruise, and maneuver conditions. These results indicate an area of con-
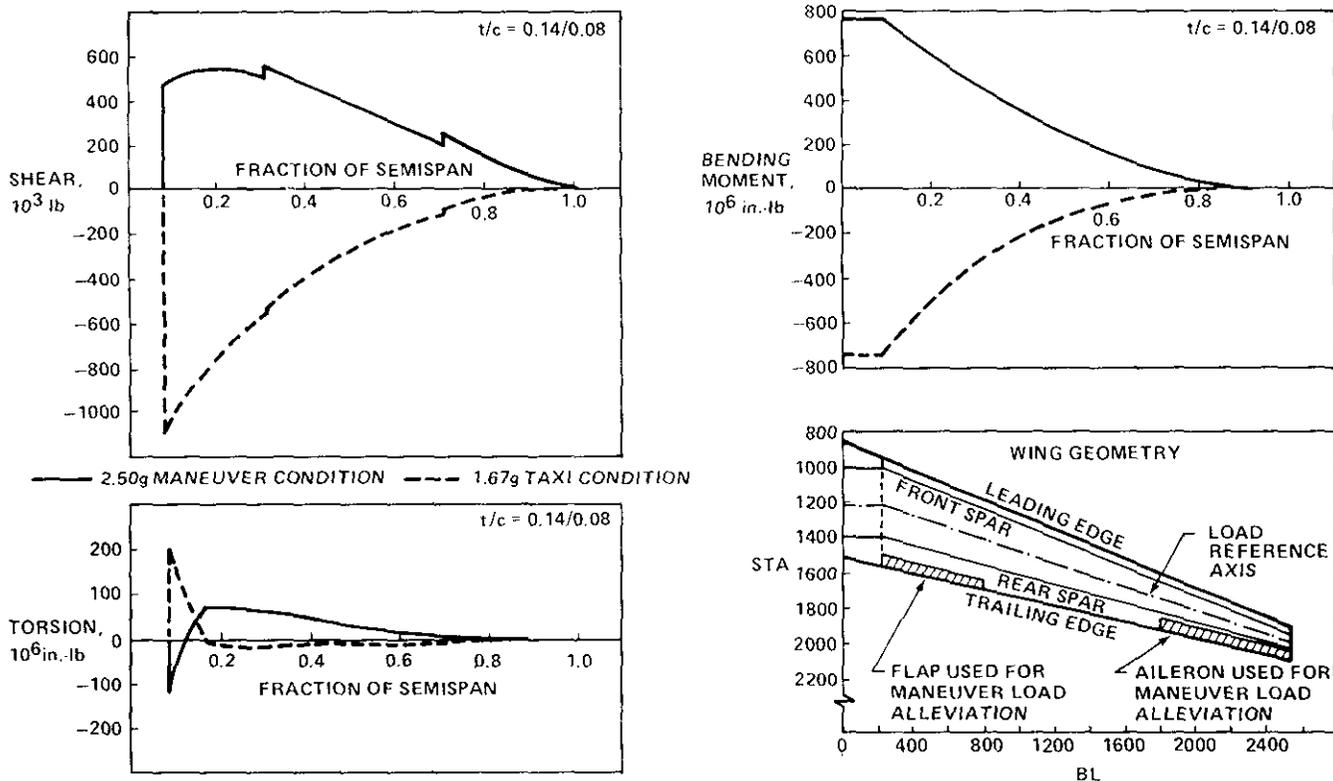

Figure 12 Cantilever Wing Structural Analyses
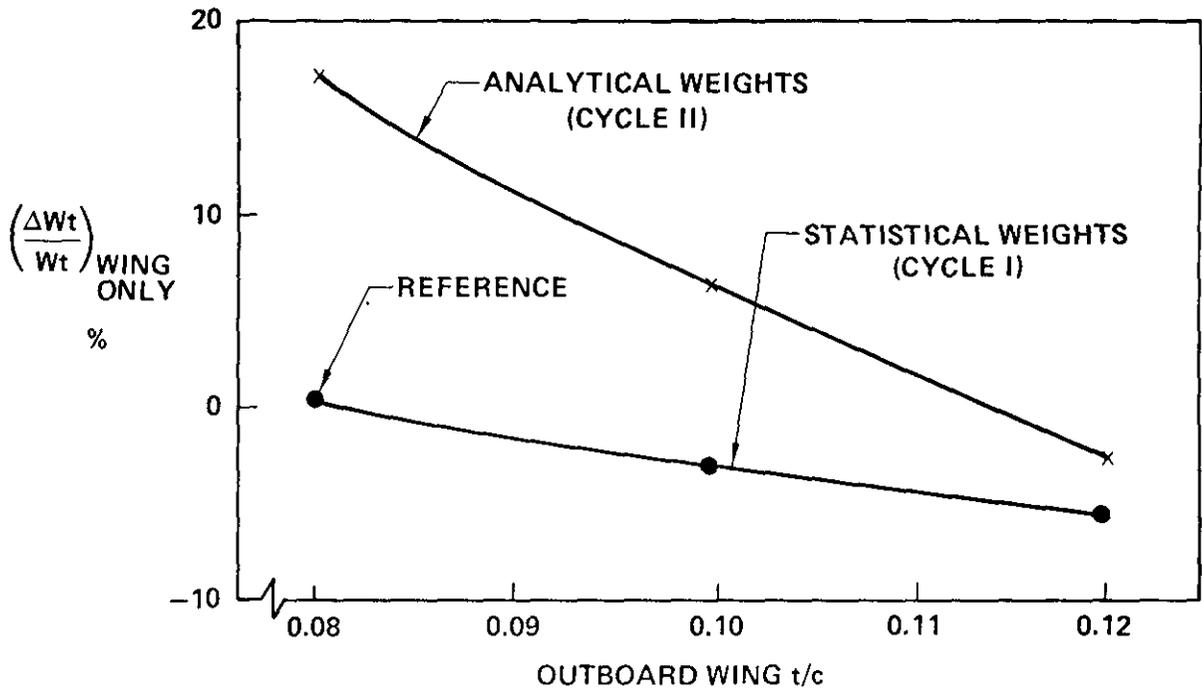
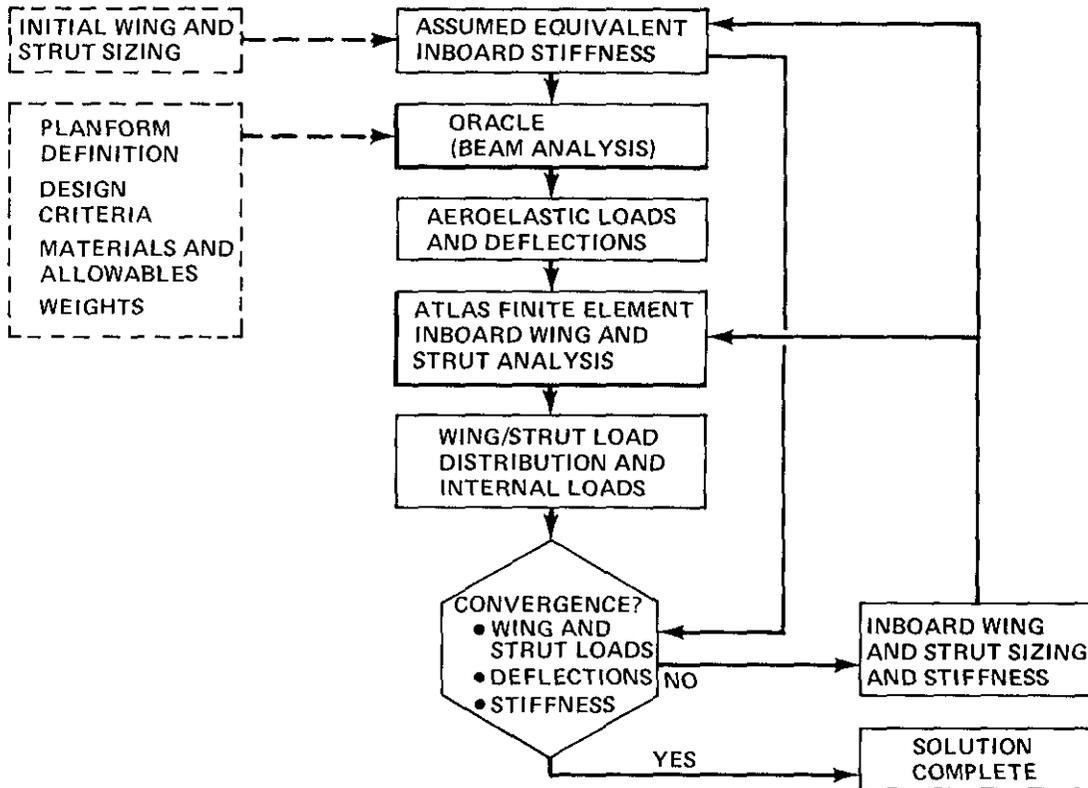Figure 13   Cantilever Wing Weight Estimates

Figure 14   Strut-Braced Wing Structural Analysis Methods
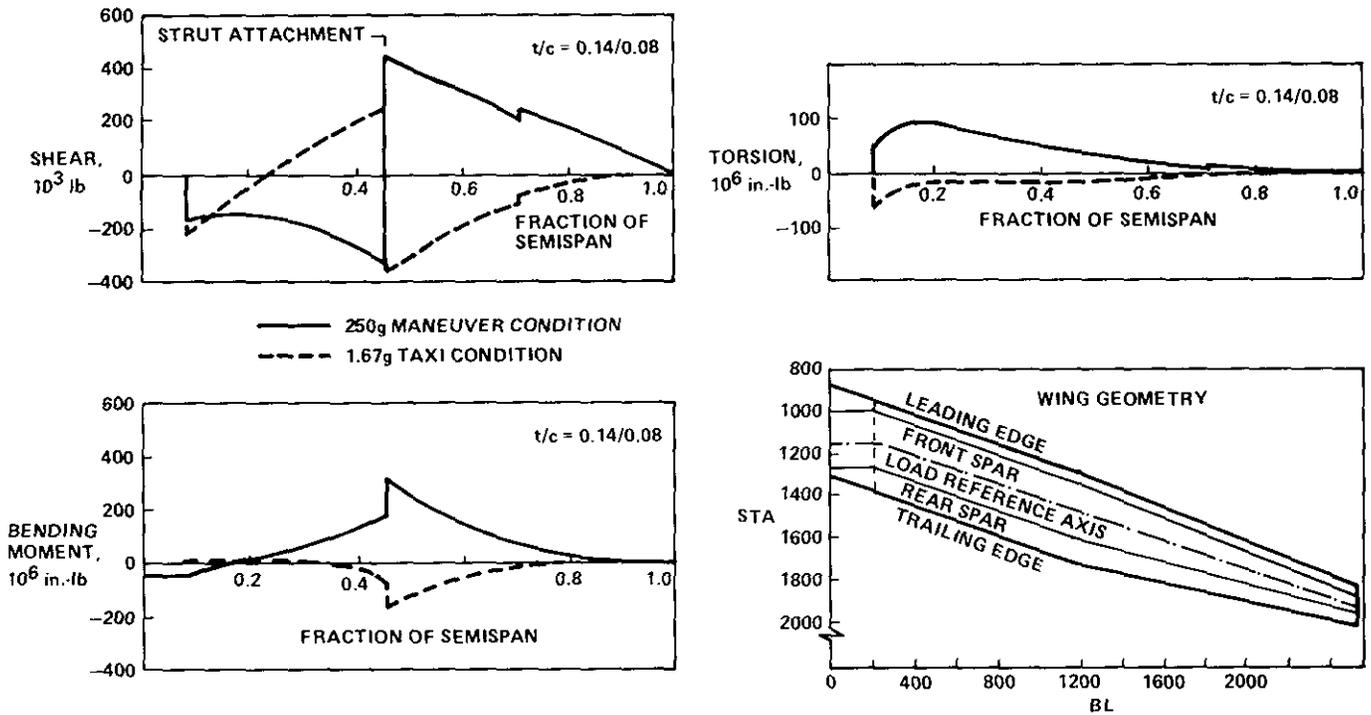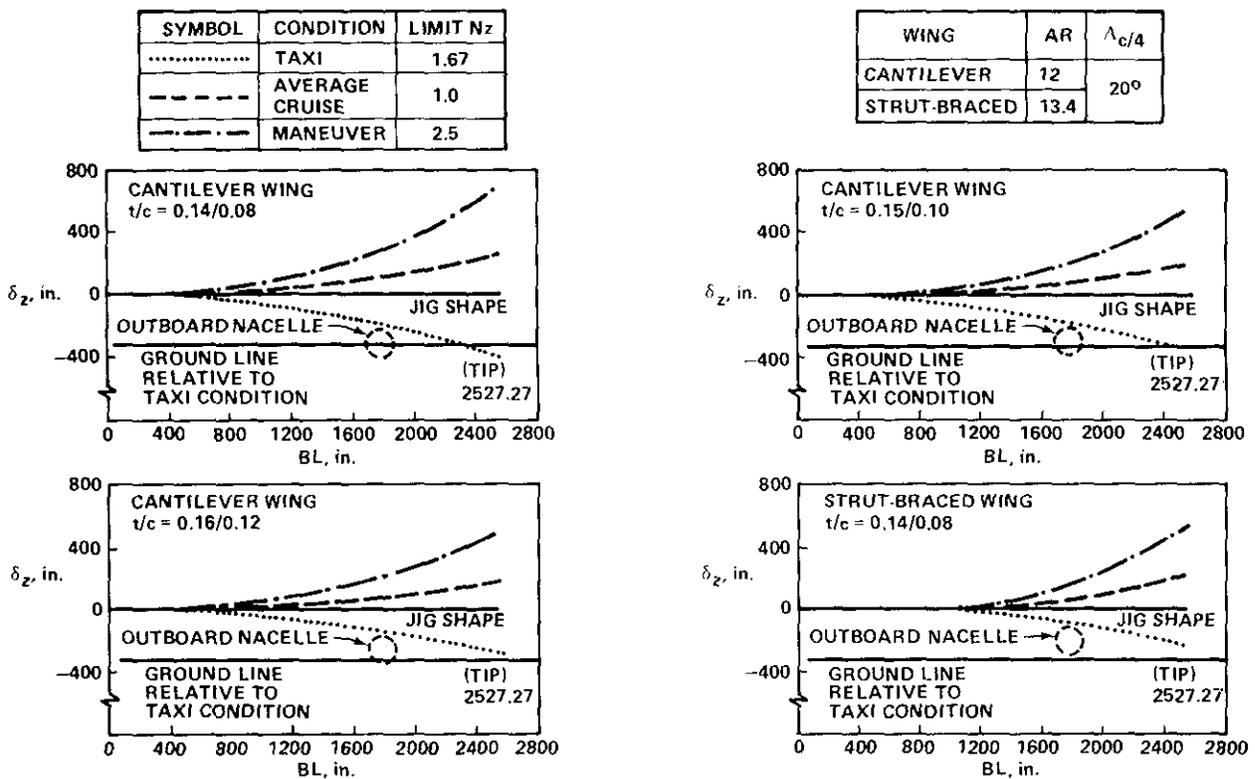
Figure 15   Strut-Braced Wing Structural Analyses

SYMBOL	CONDITION	LIMIT Nz
....	TAXI	1.67
— — —	AVERAGE CRUISE	1.0
—·—·—	MANEUVER	2.5

WING	AR	$\Lambda_{c/4}$
CANTILEVER	12	20°
STRUT-BRACED	13.4	

Figure 16   Large-Span Wing Deflections

cern in the taxi condition, where the tip and/ or outboard nacelle strike the ground. Increased wing thickness alleviates but does not cure this problem. Additional design modifications and studies would be necessary to define the most desirable solution. The strut-braced wing concept eliminated taxi deflection concerns of all the large-span wings that were considered.

The impact of the differences in wing weights estimated by statistical methods and by analytical methods on the fuel consumption, empty weight, and gross weight of the study airplane is discussed in Section 5.0.

5.0 Weight and Performance Comparisons

Weight of the large-span wings was a major area of uncertainty, due to the use of advanced composites materials, projected use of load relieving devices, extrapolation of the weights data base, etc. Consequently, sensitivity studies were made to determine the effects of variations of wing weight on the gross weight, fuel consumption, and size characteristics of the cantilever wing and strut-braced wing configurations. Results are shown in Table 2 as sensitivities expressed as percentage change in fuel, gross weight, etc. for a 10% change in base wing weight. A 10% variation in base wing weight changed fuel consumption and gross weight of the airplanes by approximately 4%. The strut-braced wing airplane was less sensitive to wing weight variations in all cases, because the wing was a smaller percentage of the TOGW (13.1% for the cantilever versus 12.5% for the strut-braced).

Table 2   Airplane Sensitivities to Wing Weight Variations

| QUANTITY | PERCENT CHANGE FOR A 10 PERCENT INCREASE IN WING WEIGHT | |
	CANTILEVER WING AIRPLANE AR = 12 t/c = 0.14/0.08	STRUT-BRACED WING AIRPLANE AR = 13.4 t/c = 0.14/0.08
EMPTY WEIGHT:		
—UNCYCLED	3.3	3.2
—CYCLED	7.3	6.3
GROSS WEIGHT	4.2	3.4
FUEL BURNED	3.4	2.6
THRUST REQUIRED	4.1	3.4
WING AREA ·	4.2	3.5

Detailed structural analyses were used to develop analytical weight estimates of the cantilever wing and the strut-braced wing. The cantilever wing configuration and the strut-braced wing configuration were then resized with these wing weights determined by the structural analyses. Additional structural analyses were made to determine the effect of wing thickness distribution on wing weight. Effects of wing thickness on the gross weight, fuel consumption, and operational empty weight (OEW) of the cantilever wing configuration are shown in Figure 17. Statistical weights indicate that the 0.14/0.08 thickness/chord distribution minimizes fuel burned, OEW, and gross weight. Results of the analytical weights evaluation showed that the weight of the thinnest wing was 18% heavier
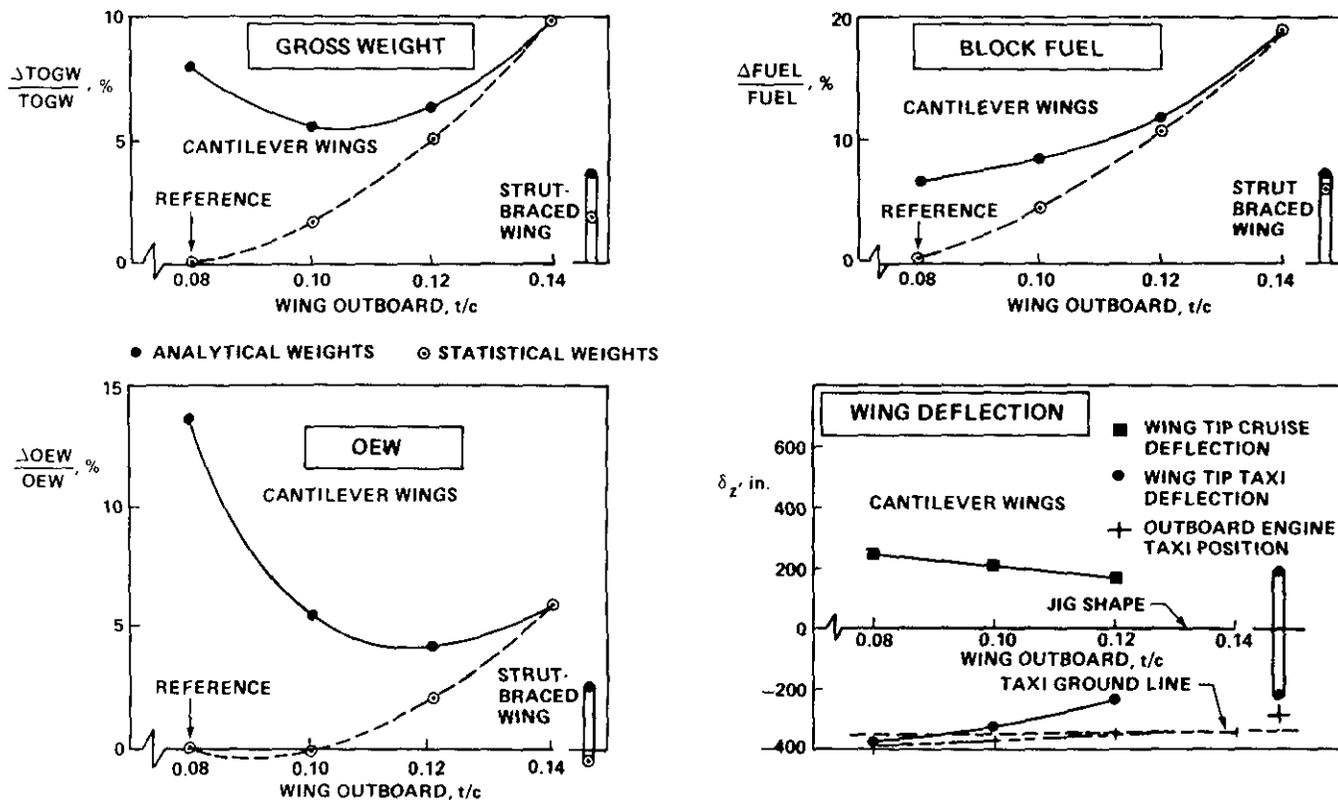

Figure 17   Large-Span Wing Comparisons

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than indicated by the statistical weights, while the weights of the thickest wings were nearly equal (Figure 13). Consequently, results obtained with the analytical weights indicated that minimum fuel consumption is still obtained with the thin wing. However, thicker wings are required to minimize operational empty weight and gross weight. The minimum TOGW is achieved by increasing the wing thickness ratio to 0.15/0.10. This increase reduces the cruise speed to M = 0.76. A further increase to t/c = 0.16/0.12 is required to minimize empty weight, and the cruise Mach number for this thickness would be further reduced to M = 0.74.

Analytical weight evaluations of the strut-braced wing indicated that the wing weight was higher than had been predicted by the statistical weights, but the relative weight increase was not as great as for the comparable thickness (0.14/0.08) cantilever wing. Hence, the more accurate analytical weights showed that the strut-braced wing airplane required 1.6% less fuel, 1.8% less gross weight, and 3% less empty weight than the cantilever wing airplane with the best wing thickness distribution of 0.15/0.10. Figure 17 also emphasizes that the strut-braced wing is effective in reducing wing taxi deflections to an acceptable level.

Cruise drag comparisons of the final-sized cantilever wing and strut-braced wing configurations are show in Figure 18. The high aspect ratio of the strut-braced wing decreases induced drag, C_{D_i}. The profile drag increases because of the strut drag and strut interference effects. The drag polars approach the same levels at high-lift coefficients, C_L. The cantilever wing and strut-braced wing configurations have relatively high lift/ drag ratios (27.8 and 26.7 respectively), because of the large wing span to wetted area ratios.

Bar chart comparisons of the configuration gross weights are shown in Figure 19. Initial comparisons based on parametric statistical weights indicate that the gross weight of the cantilever wing airplane is slightly less than that of the strut-braced wing airplane. Airplane evaluations using weights based on detailed structural analyses, however, indicate that the strut-braced configuration has approximately 4% less gross weight than the cantilever configuration.

Economic analyses were made to determine the 20-year life-cycle costs (112 unit-equipped airplanes operating 1,080 hours each) and surge condition (10 flying hours per airplane per day for 60 days) operating costs. Production costs are the major portion of life-cycle costs (40%), while fuel costs are a relatively small portion (15%), because of the low utilization rate. For the surge condition utilization rate, fuel costs comprise over 50% of operating costs. Cost comparisons based on the statistical weights indicate that operating costs and life-cycle costs of the cantilever wing configuration are slightly less than for the strut-braced configuration. The analytical weight evaluations indicate that the gross weights of the strut-braced wing configuration are less than those of the cantilever wing configuration and, since cost is based on weight, the operating and life-cycle costs of the strut-braced configuration would actually be the smaller. However, to fully determine the performance and economic potential of the strut-braced wing configuration, coordinated detailed structural and aerodynamic studies are necessary.
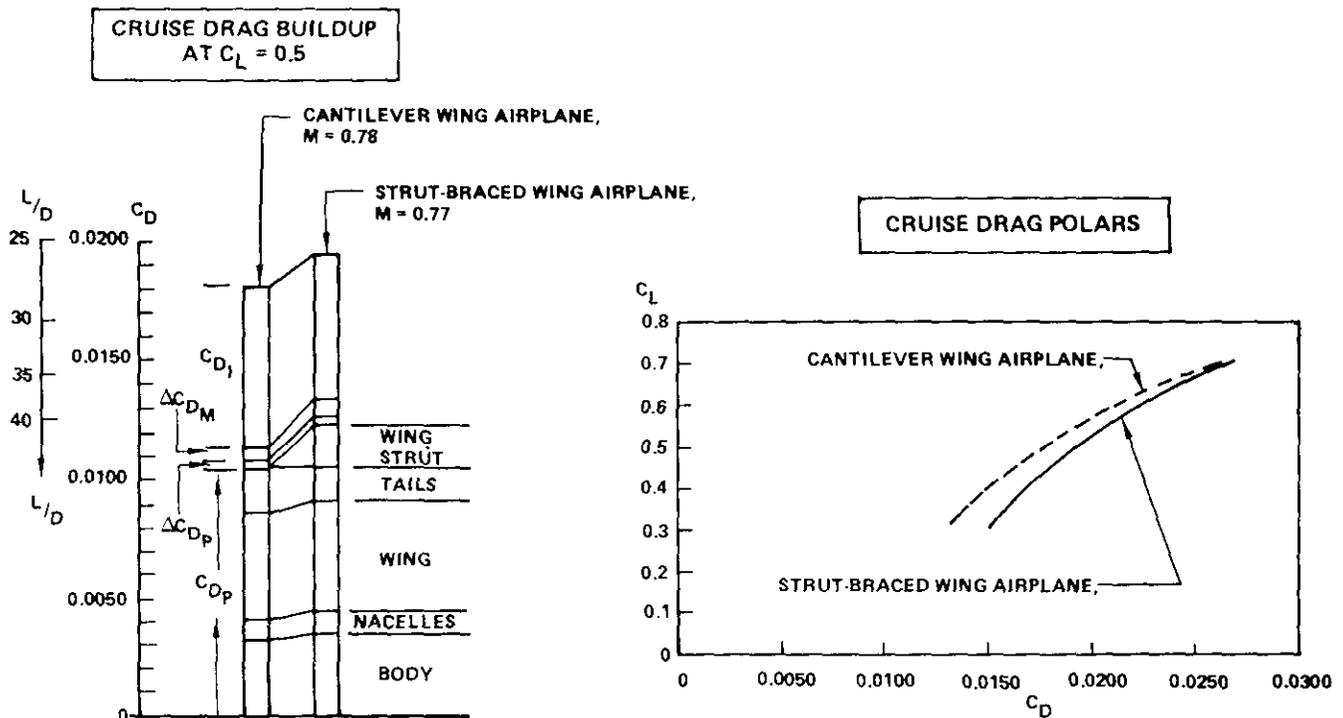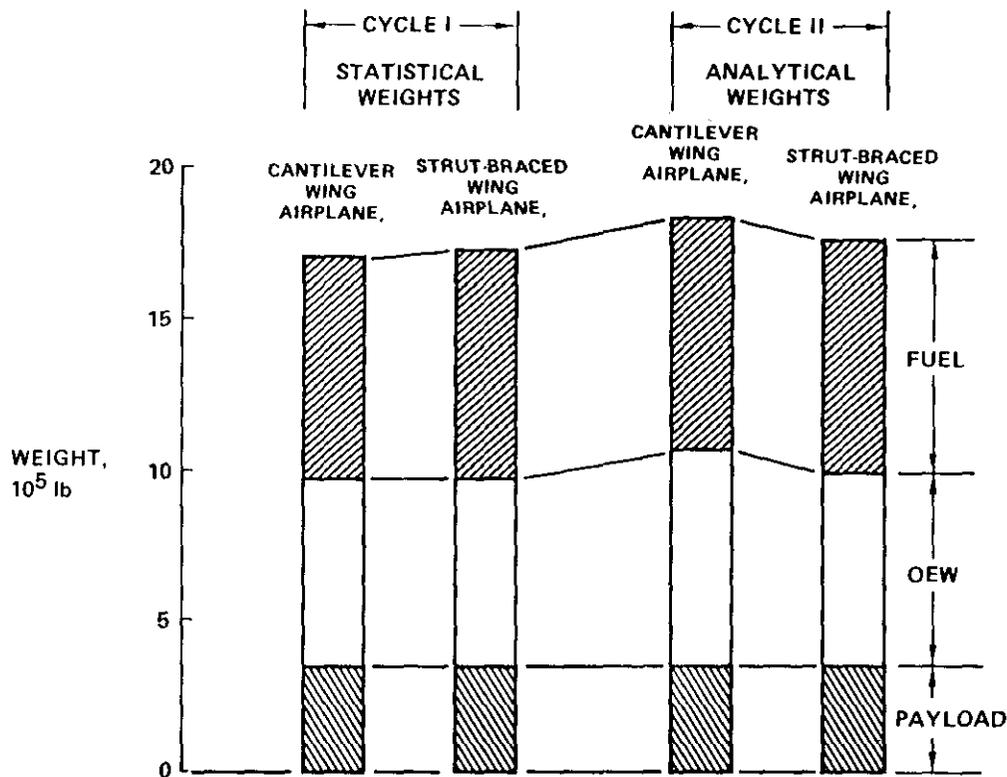

Figure 18   Cruise Drag Polar Comparison

Figure 19 Gross Weight Comparison

Conclusions

The conclusions that apply to very long-range, high-payload military transport airplanes of relatively low utilization are given below.

- Based on parametric statistical weights, the best cantilever wing planform for minimum TOGW and minimum fuel requirements had a high aspect ratio, low sweep, and low thickness/chord ratio.

- More accurate analytical weights confirmed the parametric statistical weights result that the thinnest wing minimizes fuel. However, the minimum TOGW was achieved by increasing wing thickness ratio, and minimum OEW occurred with the wing thickness ratio further increased.

- Structural analyses indicated that very large-span cantilever wings experience unacceptable deflections. Increasing the wing thickness reduced the taxi condition deflections at the expense of increased fuel requirements and reduced cruise apeed. The strut-braced wing design reduced taxi deflections to acceptable levels.

- Based on analytical (structural analyses) weights and projected improvements in wing/strut aerodynamic designs, the strut-braced wing offered the potential of lower TOGW, OEW, and fuel consumption.

- Additional detailed structural and aerodynamic design, analyses, and testing are required to define optimum geometries and design limitations of very large-span wings.

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