Costs and Benefits of Composite Material Applications to a Civil STOL Aircraft

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Costs and benefits of advanced composite primary airframe structure were studied to determine cost-effective applications to a civil STOL aircraft designed for introduction in the early 1980 time period. Applications were assessed by comparing costs and weight with a baseline metal aircraft which served as a basis of comparison throughout the study. Costs as well as weights were estimated from specific designs of principal airframe components, thus establishing a cost-data base for the study. Cost effectiveness was judged by an analysis that compared direct operating costs and return on investment of the composite and baseline aircraft. A systems operations analysis was performed to judge effects of the smaller, lighter, composite aircraft. It was determined that broad applications of advanced composites to the airframe considered could be cost-effective, but this advantage is strongly influenced by structural configuration and several key cost categories.

Introduction

ABILITY to define costs and benefits of material applications is a prerequisite to material and design cost-effectiveness assessments. Although adequate data exist to perform successful studies for metals,[1,2] data for advanced composites are almost completely lacking.[3] The primary purpose of this study was to define costs and benefits associated with applications of advanced composite materials to civil STOL aircraft designed for introduction into service in the 1980's. Although no single study can definitively answer the broad range of questions that this topic poses, the results obtained in this investigation help to define principal cost categories and the value of weight savings, which are of key importance to the design evolution process.

Although parametric cost data can be used to screen composite-material applications,[4,5] the methodology defined in this study is based on the fact that composite costs that are scaled from historical metal cost data are inadequate to assess the cost-effectiveness of broad application of composite materials. A major effort, therefore, was undertaken to establish a cost-data base to provide comparative composite production and operating costs. Airframe manufacturing labor and material costs were emphasized since these costs, as for conventional metal structures, remain the most significant for the development and production phases of composite airframe construction.

Application emphasis was on primary structure, since it is expected that large-scale applications will evolve despite necessary remaining development. Design concepts considered were those which took advantage of manufacturing characteristics of composites to strike an optimum balance between weight and cost increments. The final criterion for concept selection was performance in a total system economic environment.

For practical applications of advanced composites, it is essential not only to isolate areas of cost-effective applications, but to define the design concepts for those applications. Concepts chosen for detailed study are somewhat conventional in appearance, but were configured to take full advantage of advanced composites. As part of an intensive design study, additional concepts which represented wide departures from conventional configurations were considered, but generally were found to offer little or no advantage. Thus, designs that fully exploit advanced composites need be neither complicated nor highly complex, and the so-called "aggressive" designs, sometimes advocated as necessary to fully develop composites may be undesirable from a practical point of view.

Results reported in this paper are detailed in Ref. 6 and 7. The final report[6] also includes results of parametric and sensitivity analyses for key cost parameters for the aircraft studied. It is to be noted that operating cost sensitivity to changes in aircraft parameters is highly dependent on aircraft configuration, route structure, and cost basis assumption. Thus, results presented in this paper are strictly applicable only to the specific class of STOL aircraft studied, although broad conclusions appear to be generally applicable. Detailed descriptions of the baseline aircraft, as well as performance and systems analyses, are contained in the final reports[8] of an overall systems study.

Study Methodology and Overview

The methodology was developed to generate principal manufacturing and operating costs which are affected by use of advanced composites. Emphasis was on development of comparative weights and costs, relative to a baseline aircraft.

Airframe Cost Analysis

With selection of a baseline study aircraft, costs of items which would not be directly affected by applications of composites were determined, using historical cost data. Included were such items as avionics, which were assumed to have the same costs for both the baseline and the composite aircraft, and landing gear assemblies, which have costs that changed only with aircraft weight changes.

Items which would have costs directly affected by composite applications were mainly airframe components, and for purposes of this study, these airframe components were separated into three groups: primary structure, secondary structure and major control surfaces, and remaining structure. These groups are illustrated in Fig. 1. The first group includes wing and empennage structural boxes, and the fuselage shell; the second group includes flaps, floors, and fairings; and the third group includes control surfaces, high-lift devices, and nacelles.

Components of the first group comprise 54% of the airframe weight of the study aircraft, and were investigated in detail. The second group of components has less potential for

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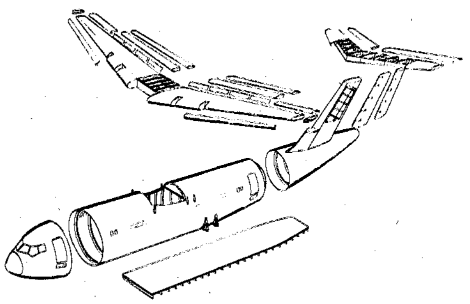

Fig. 1 Component and subassembly breakdown.

weight saving, and was developed to a lesser level of detail. The third group was evaluated principally by comparison with other studies.

The baseline aircraft definition included design loads, base weights for all items, and base costs. Competitive structural concepts were evaluated through a series of trade studies, resulting in the most cost/weight competitive designs. The selected concepts were subjected to layout and design studies which resulted in Manufacturing Cost Estimating (MCE) drawings that provided the basis on which airframe weights and manufacturing costs were derived.

To these costs were added all other costs necessary to assess the impact of composites, including maintenance, engineering, and an assessment of required research and development. The method was developed to provide weight and cost increments, resulting from application of advanced composites, with a level of detail and accuracy commensurate with the relative importance of the particular weight or cost category. All costing was performed on the basis of a total production of 400 aircraft.

Weight Analysis

Typical weight assessment procedures for material application studies utilize ratios based on material mechanical properties,[1,9] or on design and analysis of typical components.[10] The first method can be useful for investigating a broad range of applications, or for screening processes.[11] However, for detailed assessment of a specific aircraft configuration, development of weights from actual designs is preferred[12,13] so that effects of loads, layup patterns, and design configurations can be considered.

Baseline metal aircraft weight were based on historical parametric data. Eighty-five separate weight categories were used in order to include effects of structural detail variations of major components. Major composite component weights were obtained by direct weight estimation of the MCE drawings. Weights of the second and third component groups were estimated from drawings less detailed than the MCE drawings, and by comparison with prototype parts. Weight increments to reflect nonoptimum design of composite components were estimated to assure that the composite weights would be realistically comparable to the metal weights.

Manufacturing Costs

Manufacturing costs based on the previously described component and subassembly breakdown were determined according to the following principal manufacturing cost categories: 1) fabrication, 2) assembly, 3) tooling, 4) planning, 5) quality assurance, and 6) raw materials. Based on metal production cost data, fabrication and assembly material and labor can comprise 60 to 80% of the total production costs for an aircraft fleet. With the anticipation that the same relative importance also would hold for composite-structure production costs, primary emphasis was placed on those categories.

To assess composite manufacturing costs more accurately and to define principal cost categories, manufacturing costs were segregated to reflect composite peculiarities, with initial and sustaining portions estimated separately as appropriate. Costs of each specific application were built up by establishing costs for each subelement. A tool assessment was projected based on a production rate of two aircraft per week. Major facility costs were assumed to be amortized at the same rate as facilities for conventional metal aircraft.

On the basis of the MCE drawings, production rate, and tool production capabilities, a manufacturing planning outline was prepared, detailing sequential operations of component fabrication, bonding of individual substructure assemblies, and assembly and final inspection of the major substructural components to the complete aircraft. Preliminary manufacturing instruction sheets were prepared which provided a manufacturing outline containing fabrication, machining, subassembly, and final assembly operations. Standard hour estimates were developed from these detailed plans, without reference to the equivalent metal design or to cost history for metal structures, except where applicable to a specific metal detail.

Some component fabrication cost elements could be estimated from fiberglass experience, whereas others were estimated from past experience with prototype advanced composite parts. Thus, for example, cleanup and mold preparation costs were based on fiberglass cost data, since these operations are relatively unaffected by graphite reinforcement. On the other hand, machining cost are affected by advanced composite materials, and these were based on prototype and test data, projected into a production environment. Machine layup of major components was assumed, with material layup costs based on an established machine layup capability (12-in.-wide tape, 60 ft/min nominal head speed) and detailed consideration of each major part, including tape cutting and head indexing time. Costs of subassembly and final assembly of the major components were estimated from consideration of time to perform detail operations, aided by applicable historical fiberglass and advanced composite data.

Raw composite material costs were obtained from a survey of supplier data and published studies, and were extrapolated to 1980 using estimates based on historical trends and assuming high-volume usage. Principal material form used was unidirectional tape. Material utilization factors were developed to estimate the amount of raw material required for a given part weight, and included effects of trim loss, resin loss, quality control specimens, and part scrap factors. Typical utilization factors ranged from 1.4 to 1.6 and are reflected directly in total raw material cost.

Aircraft Costs

Aircraft costing was centered around the manufacturing costs just described. Aircraft production costs were considered to the following level of detail: 1) manufacturing, 2) engineering, 3) flight test, 4) laboratory test, 5) development support, and 6) avionics subsystems. Each of these costs was broken into development and sustaining portions where appropriate. As described, program emphasis was on the manufacturing cost components, and remaining cost items were developed to a level of detail sufficient to assure their proper magnitude in relation to total costs.

Benefit Analysis

In order to measure the full impact of composite applications, the entire life cycle was considered so that all costs and benefits accumulated during the life of the aircraft could be assessed. Life-cycle costs represent the sum of all anticipated expenditures required from system acquisition through retirement. These expenditures are measured by total operating costs (TOC), which consist of direct operating costs (DOC) and indirect operating costs (IOC). To judge the cost-effectiveness of composite applications, operating costs were supplemented by return on investment (ROI) data. A discounted cash-flow ROI was computed, based on an estimated investment base, a STOL operation cash flow, and an assumed interest rate of six percent.

Principal DOC elements considered are 1) flying costs, 2) depreciation, and 3) maintenance. These elements were broken into subelements as appropriate. All IOC elements are essentially the same for both metal and composite aircraft and were computed on the same basis. The DOC computations were based on a modified 1967 Air Transport Association method.[14] The IOC data were based on a standard method developed jointly by Douglas, Boeing, and Lockheed. Comparisons of DOC and ROI provided the method by which the final composite STOL aircraft was compared operationally to the baseline metal aircraft.

A parametric analysis developed the impact of various levels of weight saving and cost of weight saving for competitive design concepts. These results were used to assess the worth of design concepts and material applications to the STOL system. To aid in judging the criticality of key assumptions and cost data, a sensitivity analysis was performed for key parameters, such as composite raw material price, weight saving increments, and aircraft price.

Finally, a brief systems operations analysis was performed to provide data relating the composite and baseline metal aircraft in a total system environment. The operational analyses evaluated the baseline and composite aircraft on the basis of traffic fit, costs, and profitability.

Aircraft Descriptions

The baseline aircraft used for detailed study was selected from the study of Ref. 8. The following discussion briefly describes both the baseline and composite aircraft.

Baseline Aircraft Description

The baseline aircraft is an externally blown flap, 150-passenger, 3000-ft takeoff field length configuration. The wing has 25° of sweep and a supercritical airfoil. Major control surfaces include double-slotted flaps, leading edge flaps and slats, and a double-hinged rudder. The variable-pitch, prop-fan engines have a 17.4:1 bypass ratio and a 1.25:1 fan-pressure ratio. The aircraft achieves a noise level of 96 EPNdB at a 500-ft sideline distance.

The baseline structure is a conventional aluminum design. The wing structural box is a stiffened-skin, two-spar design with internal ribs and bulkheads, and is used as an integral fuel tank. The fuselage is a semimonocoque shell with conventional skin, longeron, frame, and bulkhead arrangement. The vertical and horizontal stabilizers utilize multirib, two-spar stiffened-skin structural boxes. The horizontal stablilizer pivot fitting is integral with the vertical stabilizer rear spar. Major control surfaces typically are built up with a single spar, ribs, skins, and an extruded trailing edge.

Composite Aircraft Description

The composite aircraft was developed from the previously described baseline metal aircraft by designing major components using composite materials and resizing the resulting vehicle. Component designs resulted from trade studies which considered relative weight and cost increments. Competitive structural concepts were evaluated and selected on the basis of DOC. The general arrangement is similar to the baseline airplane and maintains the high-wing, T-tail configuration.

Primary study emphasis was placed on an all-composite structural configuration, with secondary emphasis on a structural configuration which utilized a reinforced metal fuselage and composite wing and tail structure. General structural details of the all-composite design are shown in Fig. 2. As in the baseline aircraft, the wing has 25° of sweep and a supercritical airfoil. Furthermore, the same types of control surfaces as the baseline aircraft are used. Engines similar to the baseline engines are used; they maintain the same bypass and fan-pressure ratios as the baseline engines, and meet the same

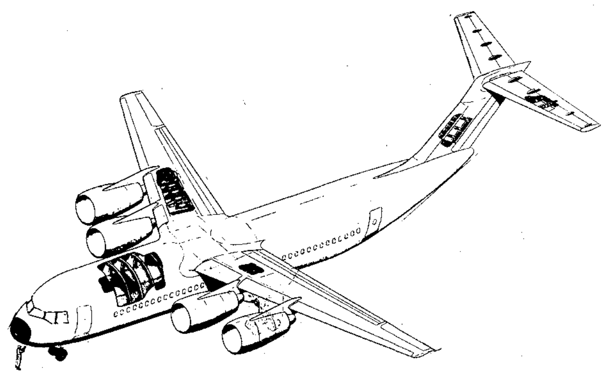

Fig. 2 Composite airplane structural arrangement.

noise requirements, but are smaller because of decreased thrust requirements.

The principal composite material considered in the study was graphite/epoxy. The selection was made principally on the basis of lower projected raw material cost and somewhat lower anticipated fabrication costs compared to boron/epoxy or metal matrix materials. Where the lower mechanical properties provide acceptable performance, fiberglass epoxy was used because of its lower cost and good formability. Additionally, PRD-49 was used in some areas where lack of compression properties was not critical.

The basic structure was developed from honcycomb sandwich panels with aluminum honeycomb core. Final assembly joints are bolted only, major fittings are bolted and bonded, and secondary joints are bonded only. All major fittings are metal. The wing box utilizes a multirib substructure with sandwich upper and lower skins. Ribs, bulkheads, and spar webs are sandwich construction. Major bulkheads have extruded-aluminum caps, whereas secondary ribs have formed graphite/epoxy attachment angles. The wing inboard leading edges, tips, and leading-edge slats are conventional aluminum construction because of lightning and environmental protection requirements.

The fuselage is built up from a graphite/epoxy, aluminum honeycomb core sandwich shell supported by composite frames. Major landing gear and wing attachment frames are aluminum with upper and lower composite segments. The floor is conventional aluminum design utilizing some boron-reinforced components. Primary cockpit enclosure structure is conventional aluminum construction. The horizontal and vertical stabilizer structural boxes are essentially the same as for the wing.

An alternate structural configuration utilizing a reinforced metal fuselage is based on a skin-stringer conventional metal fuselage. Stringer flanges, frame caps, and floor stiffeners are assumed to be infiltrated with boron/epoxy.[15] All components other than the fuselage are identical in concept to the dpreviously described all-composite aircraft, except for size.

Weight Analysis

Detailed weight analyses were performed on the baseline and composite aircraft, with results summarized in Table 1. Total weight saving in takeoff gross weight (TOGW) is 11.2% for the resized composite aircraft. For the airframe, taken to consist of the wing, fuselage, empennage, and propulsion groups, the weight saving is 22.1%. The TOGW of the reinforced-metal fuselage aircraft is 135,990 lb. which represents an 8.7% weight saving.

Table 2 summarizes materials used for the wing, fuselage, and empennage of the composite aircraft. Although the aircraft developed may be considered to be an all-composite design, it is only 40%wt composite material. Of the total composite weight, 79% is graphite/epoxy. Variations in percentages of materials used are primarily due to allocation of detail parts and design configurations. Primary structure portions of the four components listed account for 72% of the

Table 1 Weight comparisons

Component	Baseline aircraft	Resized weight, lb: All composite aircraft	Resized weight, lb: Reinforced metal fuselage aircraft
Wing	18,070	12,798	13,282
Fuselage	23,405	19,531	21,824
Horizontal tail	2,580	1,809	1,849
Vertical tail	2,045	1,235	1,282
Propulsion	18,691	15,086	15,434
Systems, misc.	37,819	36,681	36,917
Operator's empty weight	102,610	87,140	90,588
Payload	30,000	30,000	30,000
Fuel	16,390	15,160	15,399
Takeoff gross weight	149,000	132,300	135,987

total weight saving and utilized 83% of the total composite material in those components. The ratio of weight saved to weight of composite material was 0.96 for the wing box and 0.52 for the fuselage, reflecting more efficient material usage in the wing box, where the loads are higher and fewer minimum-gauge areas are encountered.

Cost and Benefit Summary

Costs for the aluminum and composite aircraft were developed, and benefits assessed on the bases that were previously described. Single-point estimates were generally developed, except that a range of raw material prices was specifically considered because of its potential impact on study results. Impact of other variables was investigated parametrically, as discussed in a subsequent sensitivity-analysis section. Although the cost data discussed are based on assessments of specific designs, interpretation of the data should be extendable to other aircraft systems to indicate general trends.

Airplane Cost/Price Summary

For raw materials, a range of prices was assumed which resulted in three cases, or a price range, for the airplane. They are low, nominal and high ($10, $25, and $30/lb respectively). The overall price comparison of the airplane is shown in Table 3, where the airframe price variation is due to the raw-material price variation. The engine was not included in the detailed analysis for composite applications; engine cost and weight data were taken from other programs. These prices include all of the resource elements normally contained in the nonrecurring and recurring cost categories.

Costs for the reinforced-metal fuselage configuration were assessed parametrically using the previously discussed data for the composite portions, and were based on an average unit weight cost of major components. Costs for the fuselage were assumed to be the same, on a unit weight basis, as conventional metal construction, except material costs, which were estimated separately. Material costs for conventional portions were estimated from well-established historical data, whereas cost for the boron-infiltrated subcomponents were estimated as $26/lb.

Table 3 Price comparison of metal and composite aircraft[a] (10^6 1972 dollars)

Aircraft subsystem	Baseline metal aircraft	Composite aircraft: Low	Composite aircraft: Nominal	Composite aircraft: High
Airframe	7.691	7.433	7.748	7.873
Avionics	0.628	0.628	0.628	0.628
Engines	3.212	3.124	3.124	3.124
Total unit price	11.531	11.185	11.500	11.625
Price 400 aircraft	4612	4474	4600	4650

[a] Total unit price for reinforced-metal fuselage aircraft = 11.3×10^6 for nominal material price, 11.1×10^6 for low material price. 11.4×10^6 for high material price.

Table 4 Airframe cost element comparison

Resource element	Total 1972 dollars $\times 10^6$: Baseline metal aircraft	Total 1972 dollars $\times 10^6$: Nominal composite aircraft[a]
Engineering	0.675	0.708
Development support	0.076	0.075
Test flight and laboratory test	0.149	0.165
Manufacturing	3.085	2.925
Tooling	0.726	0.574
Planning	0.302	0.266
Quality assurance	0.394	0.482
Raw materials and purchased parts	1.586	1.849
Total airframe	6.992	7.044

[a] All-composite configuration, based on nominal composite material price.

Table 4 summarizes production and development cost elements for the airframe items considered in this program, and compares the composite and baseline aircraft. The total airframe cost has increased by 0.7%. It can be seen that a basic reason for this slight increase in cost is the material cost which has increased by $\$0.26 \times 10^6$, offsetting the $\$0.16 \times 10^6$ decrease in manufacturing labor. Other significant elements are seen to be quality assurand tooling costs. However, the most important elements are manufacturing labor and material.

Considering material price variation, total aircraft cost for the all-composite design varied from 3.0% less to 0.8% more than the baseline design, whereas the boron-reinforced fuselage design averaged 2.0% less. In general, the prices of the three configurations appear to be nearly equal, within practical expectations of the study, even though the weights show relatively large differences. The consequences of these results appear in the opeating cost analysis discussion.

Maintenance

Airframe maintenance costs are a significant portion of total operation costs and can be strongly influenced by use of composite materials. Therefore, a detailed maintenance program was developed to reflect STOL operations[8] as well as composite applications. Costs and operational procedures that were developed for the composite STOL presumed that

Table 2 Material application weight summary (all-composite aircraft)

Item	Graphite	Boron	Fiberglass	PRD-49	Al	Ti	Steel	Core	Adhesive	Misc.	Total
	Material weight, lb										
Wing	3,998	0	430	185	6,180	551	372	753	299	30	12,798
Fuselage	5,949	83	714	1,435	4,741	32	362	2,933	1,512	1,770[a]	19,531
Empennage	1,301	0	142	0	1,176	0	42	214	107	62	3,044
Total	11,248	83	1,286	1,620	12,097	583	776	3,900	1,918	1,862	35,373

[a] Includes windows, seals.

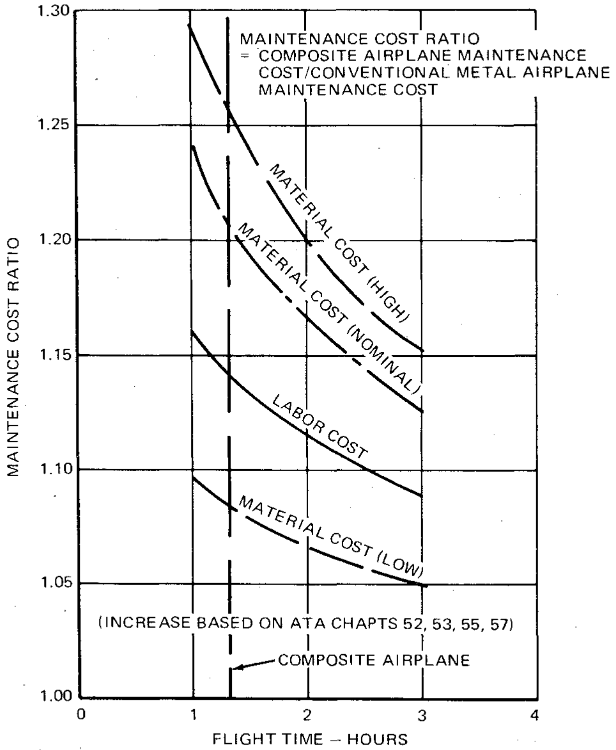

Fig. 3 Composite airplane maintenance cost ratios.

maintenance procedures, including personnel training and equipment development, would be established by the time of introduction of the composite aircraft into service.

A scheduled maintenance program was developed, which consisted of service checks, A and C checks, and a structural inspection program. Overall concepts and inspection intervals are essentially the same for the composircraft as for the bas metal aircraft. Since cost factors for structural portions of the maintenance program can be influenced strongly by composites, maintenance labor and material costs were developed for doors, fuselage, empennage, and wings, which were the major components affected by composites.

Because of the lack of flight data on advanced-composite airframes, costs of the program outlined were estimated from the results of an in-depth maintenance cost analysis[16] and also from conventional aircraft maintenance cost experience. Figure 3 summarizes the relative costs for maintenance of the specified cost categories for the all-composite configuration as a function of flight duration. The material cost variation corresponds to the range of costs previously discussed for manufacturing material. These ratios are used to estimate composite aircraft maintenance costs.

Benefit Analysis

Table 5 summarizes DOC for the two composite designs, considered as a function of both material and maintenance costs. From the results shown, it can be seen that both material and maintenance costs have significant impact on the DOC. Thus, for the all-composite aircraft, and the nominal material cost category, the DOC varies from −2.0 to +2.0% compared to the baseline, corresponding to the equivalent and estimated maintenance costs, respectively. For the reinforced-metal fuselage design, the corresponding changes are −2.5 and +1.5%. The principal conclusion that can be established from the data of Table 5 is that, for lower material and maintenance costs, the all-composite aircraft shows an improved DOC as compared to the baseline, and is approximately equal to DOC values developed by the reinforced-metal fuselage case. However, for higher maintenance costs, the reinforced-metal fuselage aircraft is slightly superior, indicating a potential for reinforced-metal construction to offer a cost-effective

Table 5 DOC comparisons (cents per available statute seat mile)

Configuration	Estimated maintenance[a]	Equivalent maintenance[b]
Baseline aircraft	1.99	1.99
All-composite aircraft		
Low material	1.98	1.92
Nominal material	2.03	1.95
High material	2.06	1.96
Reinforced-metal fuselage aircraft		
Low material	1.95	1.92
Nominal material	1.96	1.94
High material	1.97	1.95

[a]Based on Ref. 16. [b]Based on conventional metal aircraft having the same cost and weight as the composite aircraft.

design solution.[17,18] The data are, however, sensitive to key assumptions discussed in a following section.

The trend of ROI generally follows the trend of DOC, being higher than the baseline for DOC values that are lower than the baseline, and conversely. For the estimated maintenance case and nominal material costs, ROI is 15.8% for the composite aircraft and 16.7% for the reinforced-metal fuselage aircraft, respectively, compared to 16.2% for the baseline aircraft. It should be noted that the trend of DOC would generally be expected to follow the price pattern. However, for the composite aircraft cases studied, the DOC vary from −0.5 to +3.5% compared to the baseline metal aircraft, wheras the corresponding prices varied from −3.0 to +0.8%. This disparity is primarily caused by effects of weight and cost changes that are different from those for conventional metal aircraft. Thus, as previously discussed, the composite aircraft developed substantial weight saving, whereas cost were nearly equal to the baseline metal design.

A systems operations analysis for the composite aircraft was performed based on the procedures developed for the baseline metal aircraft. Motivation for the analysis was to study impact of the smaller, resized composite vehicle on key operational aspects to determine if there were any important effects of the composite airplane not included in the previous economic measures. Included were fleet requirements, airline airport operational equipment, airport evaluation, operations evaluation, noise impact, and fleet operations.

No major difference was found between the baseline and resized composite aircraft. The composite aircraft developed generally lower requirements for gate parking space, pavement thickness, taxiway and runway widths, block fuel, and block times. Gate requirements and taxiway runway requirement reductions were due to the shorter wingspan for the composite aircraft. Slight pavement thickness reductions and block fuel decreases were due to the lower weight of the composite aircraft. Block time differences were generally negligible, being approximately 6% maximum. The 90-EPNdB noise footprint area for the composite airplane decreased by 8.5% and, while not significant in itself, the major area reduction occurs in the takeoff lobe, where the impact would have the greatest effect in reducing noise exposure.

These operations changes were judged to be relatively insignificant to the total STOL system concept, although there could be importance in specific circumstances. For example, the decreased pavement requirements could allow operation of the composite STOL in airports without modification that otherwise would require runway strengthening.

Evaluation of Results

To provide perspective for evaluation of study results, comparisons to other similar studies and to conventional takeoff and landing aircraft were made. A parametric study was made to support the cost-weight trade studies and sensitivity studies. The parametric data were generated for both DOC

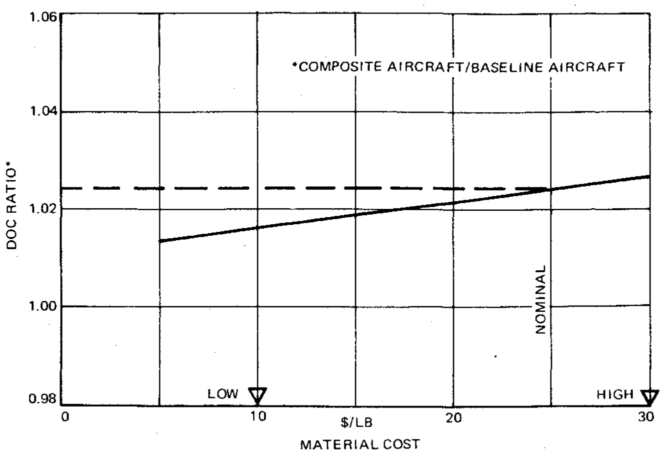

Fig. 4 Effect of graphite/epoxy raw manufacturing material price on DOC.

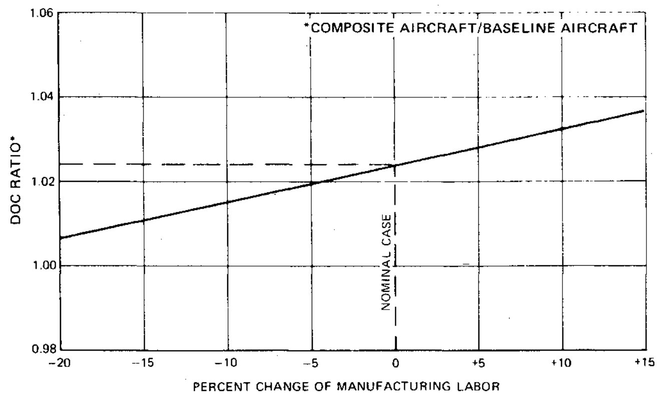

Fig. 5 Effect of manufacturing labor on DOC.

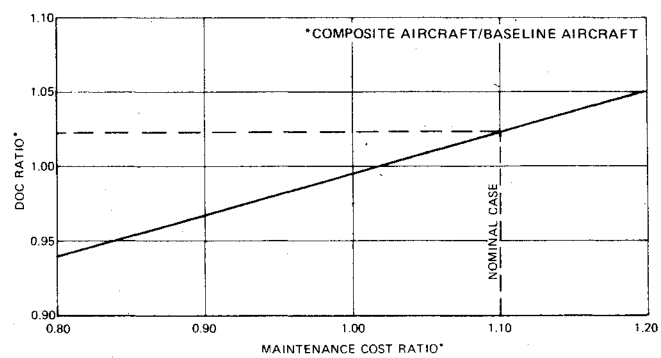

Fig. 6 Effect of maintenance cost on DOC.

and ROI by exercising the respective programs with an appropriate range of variables.

Sensitivity Study

As previously discussed, manufacturing labor and material and maintenance costs were found to be the most significant cost categories that are influenced by composite material applications. Impact of variations in price of graphite/epoxy manufacturing material is shown in Fig. 4. The DOC is seen to be moderately sensitive to composite material price for designs developed in this study when manufacturing material only is considered. For the composite aircraft, cost of composite materials represents 26.3% of total material costs. From these data, it is apparent that a material cost decrease would not in itself reduce the composite aircraft DOC to that of the baseline aircraft.

Total manufacturing labor cost has a significant impact on DOC, as shown in Fig. 5. A 10% decrease in manufacturing labor can change DOC by 0.9%, compared to the nominal composite aircraft. Since manufacturing labor represents 42% of the total airframe production cost, it is an area in which significant impact of composite applications on total system economics can be anticipated.

Reduction in total maintenance costs is seen to be significant, as shown in Fig. 6. If total maintenance costs of the all-composite aircraft are the same as the baseline aircraft, DOC would be lowered by 0.5% and, if lowered to an equivalent metal aircraft, would decrease DOC by 2.1%, relative to the baseline aircraft. The effect of these variations, to a first approximation, is linearly cumulative, so that the total effect can be directly assessed.

Weight and Cost Comparisons

The following discussion presents a comparison of the results of this study with several recent studies of the same nature. The principal comparison was made to the study of Ref. 10 and 19, which investigated costs and benefits of applications of advanced composites to Advanced Technology Transport aircraft. The study reported in Ref. 12 considered applications of composites to a V/STOL fighter, and the study of Ref. 13 considered applications to a Light Intratheater Transport. Although absolute comparisons are of questionable value, general trends can be considered in order to gain insight into advanced-composite costs and benefits.

Although structural details varied for the aircraft considered in the cited references, they were all typically "all-composite" configurations, and showed a generally high degree of overall agreement. In particular, the amount of weight savings is consistently in the range of 20 to 30% for major components, with commensurate changes in TOGW. Thus, the anticipated range of weight savings that can be obtained by use of composites in major airframe components seems to be relatively well established.

Furthermore, generally good agreement was found in the cost of composite airframes as compared to metal airframes, in that the costs of both were approximately the same. Specific costs varied widely, however, although the primary production costs, which are manufacturing labor and material agreed rather well. These are also the areas of greatest experience to date with advanced composites. Significant disagreement was found, however, in some operating cost categories, particularly maintenance costs. This area is currently the area of least experience with advanced composites, and is consequently the area most lacking in definition. Since maintenance costs can significantly alter study results care should be taken when interpreting results.

A further brief parametric comparison was made between a long-range and a short-range aircraft, both conventional takeoff and landing (CTOL) configurations. It was found that weight savings for long-range aircraft have a greater value than for short-range aircraft, whereas the reverse is true for aircraft price decreases. Differences were only slight, however, and were quite small when the aircraft were assumed to operate off their design ranges. However, the result implies that composite applications to STOL aircraft should emphasize cost savings, whereas applications to long-range aircraft should emphasize weight savings. Significance of the result is tied to the potential of a coming generation of STOL aircraft, since to date, little emphasis has been placed on low-cost advanced-composite structure.

Conclusions

A detailed cost and weight analysis was performed on a specific STOL configuration designed with advanced-composite primary airframe components. Substantial weight savings were developed, and some improvements in direct operating costs and return on investment were obtained, as compared to a baseline conventional metal design. Comparisons to other studies indicated a general agreement with regard to amounts of weight savings and overall aircraft cost. It was established that broad applications of advanced composites to primary airframe structure can be cost-effective, but the degree of improvement is highly sensitive to maintenance and manufacturing labor costs.

Maintenance costs for the composite aircraft were found to be the least well-known and yet one of the most significant cost items influenced by composite materials, and can influence configuration selection. Composite airframe fabrication and assembly labor costs were found to be the most significant production costs that can be influenced by composite materials. Although results are based only on limited study and do not have actual cost data validation, they are anticipated to be sufficiently valid to define overall trends and to indicate areas where further study is required.

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