COST--THE CHALLENGE FOR ADVANCED MATERIALS AND STRUCTURES

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Abstract

In the mid 1980's, materials, manufacturing, and structures engineers were forced to design for reduced cost instead of reduced weight. This paper provides information on cost for aircraft structures, methods for predicting cost, and concepts for reducing airframe cost.

Introduction

The major barrier to the introduction of new materials and structure to subsonic transport aircraft is cost. Beginning with the Wright Brothers' first flight through the 1970's, reducing the airframe weight was the foremost objective for materials and structures engineers. During the early days of aircraft development, the need to reduce weight was driven by limits on power plant capability, later by the desire for improved performance, and in the 1970's by the increase in fuel prices. In the last half of the 1970's and first half of the 1980's, the technology base for aircraft structures had matured to the level of meeting the vast majority of the performance requirements needed by the world's airline companies. Political, social, and economic changes in the 1980's had significant impacts on the transport aircraft industry. The market for passenger and freight travel increased, fares were reduced, the size and cost of aircraft increased dramatically, and world competition for producing aircraft increased. Thus, by the mid 1980's, materials and structures engineers were forced to design for cost instead of weight. This change necessitated that engineers have access to cost data for identifying high cost centers for parts and assemblies. Design codes and handbooks that contain information relating cost to structural configuration, materials and material form, processing and joining methods, maintenance, and repair are becoming more available.

This paper provides information on the airframe cost for transport aircraft produced by the three largest transport manufacturers. Currently available methods for predicting airframe cost and the need for methods that are more suited for use by airframe designers during conceptual and preliminary design are discussed. Concepts for reducing airframe cost are also presented.

The reader is cautioned that values quoted or estimated herein are approximate at best. Most companies consider their cost data to be extremely proprietary. Assuming that a company must make a reasonable profit to stay in business over a long period, it is possible to estimate the current cost for aircraft structures and thus provide the target levels that new structures must meet to receive serious consideration.

Cost of Aircraft Structure

Table 1 lists the 1991 prices of eight selected commercial transport aircraft. Data sources include References 1, 2, and 3. Gross weight and operating empty weight (OEW) are listed in Columns 3 and 4. OEW is the weight of the empty aircraft as equipped for flight; it therefore includes the weight of the systems, unusable fluids and undrainable fuel, as well as the crew; it does not include the fuel weight or payload weight. The published maximum seating capacity listed in Column 5 represents an all-economy seating passenger configuration. Airplane prices range from $24M to $130M, and generally increase with increasing capacity and/or range.

Table 2 allocates total price for four of the aircraft listed in Table 1. Total price is divided into 3 parts: engines, systems, and airframe. Engines typically account for 18-24%; airframe accounts for 68-74%; and systems account for 7-9% of the total price. References 2, 3, and 4 were used to develop Table 2.

Table 3 lists estimated weight and price of airframes for all aircraft listed in Table 1. Airframe weight was calculated by subtracting total weight of engines (reference 4) and weight of systems (estimated by methods from reference 5) from OEW. The price per unit weight is listed in Column 5 in $/lb. Larger aircraft show an economy of scale relative to smaller aircraft when compared on the basis of price per unit weight. The table indicates that the Boeing 747 has a price of approximately $400 per pound, whereas the

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737 has a price of \$500 per pound, and the 757 lies between these two values. Price per unit weight ranges from \$384/lb. to \$554/lb. for all aircraft listed and the average is \$445/lb.

Table 4 provides the rationale that was used to estimate price-cost relationships for airframes. Based on Reference 6 methods, RDT&E for 300 and 200 aircraft production runs is 15% and 22% of the airframe price, respectively. A conservative manufacturer may project that only 200 aircraft will be sold and that the risk warrants 15% profit, whereas other manufacturers may develop a market strategy based on 300 aircraft sales and 10% profit. Subtracting RDT&E and profit from the airframe price yields that production cost must not exceed 63% to 75% of total price. Using the extreme values calculated in Table 3, the production cost is estimated to range from \$242/lb. to \$416/lb. Based on the average unit price of \$445/lb., the estimated range for production cost is from \$280/lb. to \$334/lb. Reference 7 indicates that approximately 80% of production cost is recurring and 20% is non-recurring. Based on the extreme values calculated in Table 3, recurring production cost is estimated to range from \$194/lb. to \$332/lb. Based on an average unit price of \$445/lb., the estimated recurring production cost is between \$224/lb. and \$267/lb.

Airframe manufactures and airline operators must also be concerned about airframe maintenance cost. References 8 and 9 list aircraft non-engine maintenance for 1990 at \$112, \$225, and \$385 per block hour for Boeing 757, 767-200 and 747-300 aircraft, respectively. The maintenance cost per pound of structure was calculated based on an assumed life of 60,000 hours and an overhead cost for facilities that equals the direct maintenance cost. Reference 10 indicates that about 20% of the non-engine maintenance is attributed to airframe structure. The calculated maintenance cost per pound of structure for the three aircraft ranges from \$37/lb. to \$49/lb. for the total service life. In reality, one would expect the maintenance cost to vary with age and be greatest near the end of the service life. The average maintenance cost is estimated to be about \$40/lb. and represents about 10% of the average acquisition price.

Value of Weight Savings

Since airframe designers must trade weight and cost to meet overall objectives, the relationship between weight and cost must be known. Three scenarios for estimating the value of a pound of weight saved in a transport aircraft are listed in Table 5. The first assumes that airframe and engines may be re-sized and fuel savings will accrue due to re-sizing. The second takes credit only for fuel savings due to reduced weight. The third assumes that the weight savings is converted to payload earnings.

The estimates presented in Table 5 were developed for a long-range transport representative of the Boeing 747 class of aircraft. The relationship between GTOW and structural weight (W_{str}) can be developed by assuming a range of 7,000 nautical miles and using gross takeoff weight (GTOW), passenger capacity, OEW and W_{str} from Tables 1 and 3 and applying the Breguet range equation (reference 11):

$$R = \frac{V}{C_f} \times \frac{L}{D} \times \ln\left[\frac{W_i}{W_{i+1}}\right]$$

where R is range, V is cruising speed, C_f is specific fuel consumption, L is lift, D is drag, Wi is initial weight or GTOW, Wi+1 is the final or landing weight. Using L/D=18, V=500 knots and C_f=0.55lb./lb.-hr in the above equation yields the following relationship

$$GTOW \cong 3.0W_{str}$$

and indicates that each pound of structural weight savings reduces the gross weight by 3 pounds.

A rough approximation of the reduction in engine weight that results can be estimated by noting:
(1) Typical thrust-to-weight ratio for this class aircraft is 0.3 and (2) Engine thrust-to-weight ratio is approximately 7. Thus, reduction in engine weight is

$$W_{eng} \cong 0.13W_{str}$$

or the engine weight may be reduced 0.13 pounds for each pound of weight reduction in the airframe. Engine cost for large turbofans was estimated to be \$650/lb. from reference 3. This would yield a reduction in engine cost of \$84 for each pound of weight removed from the airframe.

Fuel weight for the selected example is calculated to be 319,000 pounds. Thus, the relationship between fuel and structure weights is

$$W_{fuel} = 1.35W_{str}$$

The volume of fuel conserved by saving one pound of structure over the life of the aircraft is

$$W_{fuel} = \frac{1.35\text{lb}}{\text{trip}} \times \frac{1\text{gal}}{6.74\text{lb}} \times \frac{60000\text{hr}}{14\text{hrs/trip}}$$
$$= 858\text{gal}$$

Assuming fuel prices per US gallon of \$0.60/gal, \$1.00/gal and \$1.50/gal, the life savings would be

\$515/lb., \$858/lb., and \$1,287/lb. of structural weight saved, respectively. The present value of the fuel savings accrued over a 20 year period is dependent upon future interest and inflation rates. Assuming 8% per annum total rate for inflation and interest, the present value based on the 3 fuel prices is \$253/lb., \$421/lb., and \$632/lb. of structural weight saved, respectively.

Based on this elementary analysis, the value of saving a pound of structure weight is estimated to be

\$445	Reduced Average Airframe Weight
\$ 84	Reduced Engine Weight
\$253	Fuel Saving (\$0.60/gal)
\$782	Total

when the aircraft is re-sized but payload and range are held constant.

The following assumptions were used to estimate the value of converting a pound of weight saved to passenger carrying payload:

(1) Trip length of 7,000 nautical miles and 14 hours
(2) 60,000 hour airframe service life
(3) 0.65 passenger load factor
(4) 200 pound passenger and luggage

The revenue per pound of increased passenger load over the service life is given by:

$$\text{Revenue} = \frac{1\text{Pass}}{200\text{lb}} \times \frac{60000\text{hrs}}{14\text{hrs/trip}} \times \frac{0.65\text{LF} \times \text{Price/Pass}}{\text{trip}}$$

where Pass is the number of passengers and LF is the assumed average airline passenger load factor. Thus

$$\text{Revenue} = 14 \times {}^{\text{Price}}\!/_{\text{lb.}}$$

At present there is a wide range of ticket prices available. Selecting \$400, \$800, and \$1,200 for example, the revenue produced would be \$5,600, \$11,200 and \$16,800, respectively. Direct Operating Cost (DOC) for a typical 747 is reported to be \$5,500 per Block hour (reference 9). Service life DOC per pound of passenger load may be estimated by

$$\text{DOC} = \frac{\frac{\$5500}{\text{hr}} \times 60000\text{hrs}}{[0.65\text{LF} \times 516\text{Pass}] \times [200\text{lb} + 40\text{lb cargo}] / \text{Pass}}$$
$$= \$4100 / \text{lb}$$

Differences between revenue and DOC for the 3 ticket prices assumed are \$1,500/lb., \$7,100/lb., and \$12,700/lb. Current value of earnings produced over a 20-year period is dependent upon future interest and inflation rates. Assuming 8% per annum total for interest and inflation, the present value is \$744/lb., \$3,521/lb., and \$6,235/lb. for the 3 ticket prices, respectively.

Methods for Predicting Cost

Table 6 summarizes the standard methods currently used for cost/price estimating of aluminum and composite structure. The methods may be classified: financial and parametric, parametric and built-up. Variations of these methods are used by estimators and price analysts to forecast and compare the relative cost of materials, automated processes, and new structural concepts. The G.E. Price model (reference 12) is very complex, requires extensive training and is best suited to the needs of a cost analyst or accountant.

Parametric models use a regression analysis of past aircraft cost for predicting cost as a function of some aircraft design and production variables. The first publication on this type of method was in 1936. In the 1960's the Rand corporation studied several military transport and bomber aircraft using these methods. Transport-type aircraft sample sizes were small and the data collected were for older aircraft limiting the utility of the information for current studies.

In the 1970's NASA sponsored several studies that were based on commercial transport aircraft historical data. A cost model by Eide resulted from these studies (reference 6). Commercial companies have also developed cost-estimating methods based on this type of analysis and have routinely customized the models for their internal use. The basic assumption made in these parametric models is that the cost of producing aircraft structure is a function of the rate of production as well as the quantity of aircraft produced. The design variables used in the method are the maximum speed of the aircraft and the empty weight of the aircraft. The equation that expresses this relationship has coefficients and exponents which are determined by regression analysis of historical data. The resulting equation has the following form:

$$E = a \times W_e^b \times V_{max}^c \times Q^d \times P^e$$

where E represents the production hours required for manufacture, W_e is aircraft empty weight, V_{max} is maximum speed of the aircraft in knots, Q is the quantity of aircraft produced and P is the monthly production rate. Regression analyses of historical data provide the coefficients a,b,....e. Assuming a production quantity of 200 units and a production rate of 4 per month, the estimated recurring production costs of a 747 airframe with its normal systems such as hydraulics, wiring, etc., installed was approximately \$60 million. When the research, development, and test program costs are included, the estimated cost per aircraft increases to approximately $75 million. The prices for engines and avionics given in Table 2 can be used to provide an estimated cost of the aircraft at its operating empty weight condition; the result is an estimated cost of $111 million for the 747. The estimated cost without including profit is within 15% of the listed price of $130 million. A similar estimate for the MD-82 was made assuming a production quantity of 250 aircraft and a production rate of 5 per month. Estimated recurring production cost is approximately $14 million. When research, development, and test program costs, $3M, and the price of engines and avionic systems, approximately $8 million, are added the estimated total price for the operating empty weight of the aircraft is $25 million. Table 1 gives the list price of a two-year-old MD-82 as $24 million. The parametric models provide reasonable estimates for total cost but do not provide information in a format suitable for designers.

The current state-of-the-art models to estimate the cost of composite fabrication for hand lay-up and automated tape laying are the ACCEM (13) and FACET (14) programs. Northrop developed the ACCEM program in 1976 based on a time and motion study of different composite material manufacturing processes. Equations were developed to estimate recurring composite part manufacturing costs. FACET evolved from the ACCEM program with updated Air Force program databases written in FORTRAN for a mainframe computer. New material forms and manufacturing processes that can be evaluated for production of the most cost-effective structures are considered in the MIT/IBIS model (15). These Lotus 123 spreadsheet models estimate individual cost elements and enforce consistent accounting assumptions. These models provide reasonable estimates for fabrication cost but do not provide information in a format suitable for designers.

Development of Cost Models

The preliminary design period offers the best opportunity to achieve cost reduction in airframes. Industry sources indicate that 70% of airframe costs are fixed by the time the drawings are frozen and the influence of engineering on fabrication cost reductions is significantly reduced once the detailed design is completed. A comparative cost algorithm, which can function as an engineering design tool to evaluate different design concepts, is needed to guide concurrent engineering teams during design.

Efforts are underway to develop cost models that use first principles to establish building-block unit cell elements that represent different material forms, geometric shapes, fabrication processes, and methods of assembly. The goal is to express cost/pound or labor/pound with physical design and manufacturing variables that designers can visualize. This approach will provide designers with a technically sound model to predict cost and to compare competing design and manufacturing approaches. Figure 1 provides a schematic of the results of the design-with-cost process for a simple stiffened skin compression panel and indicates the type of information that cost models need to provide the designer.

Concepts for Reducing Cost

Figure 2 shows a comparison for composite and aluminum aileron assemblies for L-1011 aircraft and illustrates the advantage of tailored composites for reducing part and fastener count. The composite part provides a typical 23% weight reduction. The potential for composites is demonstrated by the 50% reduction in part count and the number of fasteners. Such savings in part and fastener count on large structure-like wings and fuselages could reduce fastener count by half a million rivets on a large wide-body class aircraft. Figure 3 shows an artist conception of a large braiding machine for manufacturing wing and fuselage assemblies. Composite structures also offer the potential for significantly less maintenance cost due to the improved corrosive and fatigue resistance.

Conclusions

1. Airframe structure recurring production cost is estimated to range between $200 and $350 per pound.

2. The value of weight savings is a function of the stage of airframe development. If payload and performance are held constant, the value may range from $800 to $6,250 depending on the assumed scenario for use of the weight savings.

3. Current cost models yield reasonable estimates for the total airframe structure cost, but are not suited for use by designers, and additional models need to be developed.

4. Automated manufacture of composite structures offers the potential to reduce weight and part count and is a major candidate for cost savings.

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Manufacturer	Aircraft	Gross Weight (Klbs)	Operating Empty Weight (Klbs)	Maximum No. of Passengers	Selling Price in 1991 $ ($M)
Airbus	A320-200	162	89	179	34
	A300-600R	378	196	375	63
Boeing	737-300	139	70	141	27
	757-200	240	126	220	42
	767-300ER	400	196	290	71
	747-400	833	390	516	130
McDonnell-Douglas	MD-82	140	79	155	24
	MD-11	618	288	410	108

Table 1. Listed Prices for Selected Commercial Transport Aircraft

Manufacturer	Aircraft	Basic ($M)	Airframe (%)	Engines		E & S*		Total
				($M)	(%)	($M)	(%)	
Airbus	A320-200	24	74	6	18	3	8	33
Boeing	737-300	19	71	6	22	2	7	27
	747-400	94	73	24	18	12	9	130
McDonnell Douglas	MD-82	16	68	6	24	2	8	24

* E & S = Equipment and Systems

Table 2. Breakdown of Listed Prices for Commercial Aircraft

Manufacturer	Aircraft	Structural Weight (Klbs)	Structural Price ($M)	Structural Price/lb. ($/lb.)
Airbus	A320-200	44	24	554
	A300-600R	106	46	434
Boeing	737-300	38	19	503
	757-200	73	32	439
	767-300ER	111	47	420
	747-400	236	94	400
McDonnell-Douglas	MD-82	38	16	424
	MD-11	173	67	384

Table 3. Aircraft Structural Weight and List Price

Number of Aircraft Produced	300	200
COST ELEMENT	(%)	(%)
Research, Design, Test & Evaluate	15	22
Production	75	63
Non-Recurring - Facilities & Tooling	(15)	(13)
Recurring - Materials, Labor, Energy, Management	(60)	(50)
Profit	10	15
Price	100	100
Recurring Production Cost for Structure, $ per lb.	$224	$267

Table 4 Estimated Percent Cost Price Breakdown for Commercial Aircraft

Scenario	Fuel or Ticket Price	Value ($/lb)
Resized Airframe & Engines and Fuel Savings	$0.60/gal	782
Fuel Savings Only due to Reduced Weight	$0.60/gal	253
	$1.00/gal	421
	$1.50/gal	632
Weight Savings Converted to Payload Earnings	$400 ticket	744
	$800 ticket	3,521
	$1,200 ticket	6,235

Table 5 The Value of Weight Savings for Commercial Aircraft Structure

NAME	CLASSIFICATION
	Financial and Parametric
G. E. Price - H	Requires detailed breakdown of the production and accounting processes. Allows risk modeling and organization. Must be customized for individual organization.
	Parametric
RAND	Regression analysis of historical cost data.
Eide, & Commercial	Regression analysis of cost data.
	Built-Up
ACCEM/FACET MIT	Requires a detailed breakdown of fabrication process and estimate labor hours on basis of 1976 time and motion study.

Table 6 Current Methods for Predicting Airframe Cost

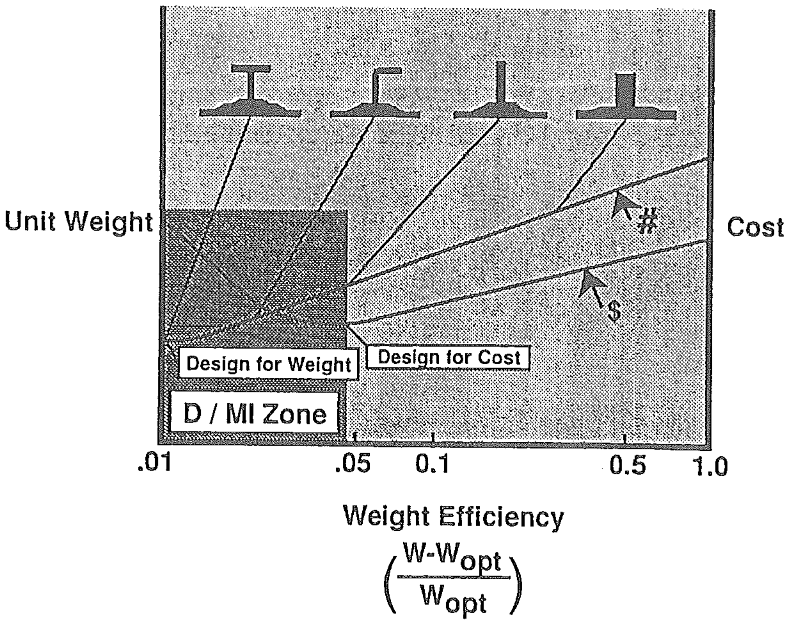
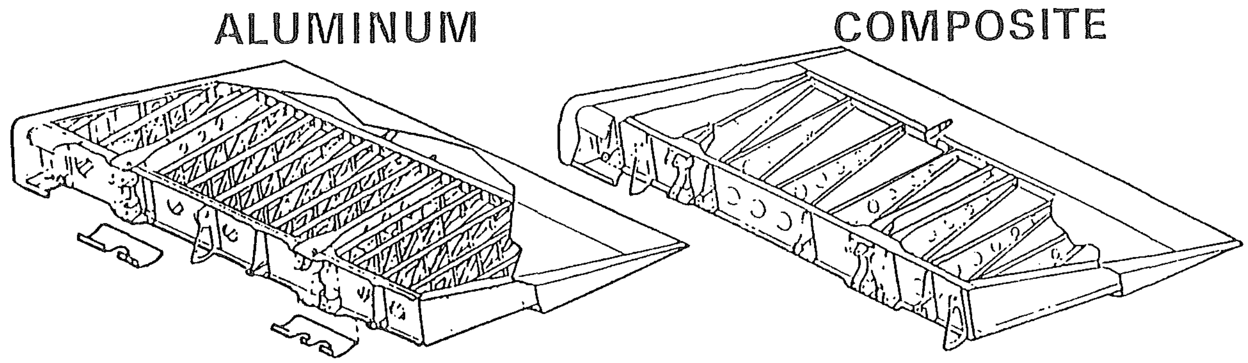


Figure 1 Design with Cost and Weight Example for Stiffened Skin Compession Panel



	ALUMINUM	COMPOSITE
WEIGHT (LB)	139.9	107.8
WEIGHT SAVED (LB)	0	32.1(23%)
NO. RIBS	18	10
NO. PARTS	398	205
NO. FASTENERS	5253	2574

Figure 2 Comparison of Composite and Metal Ailerons

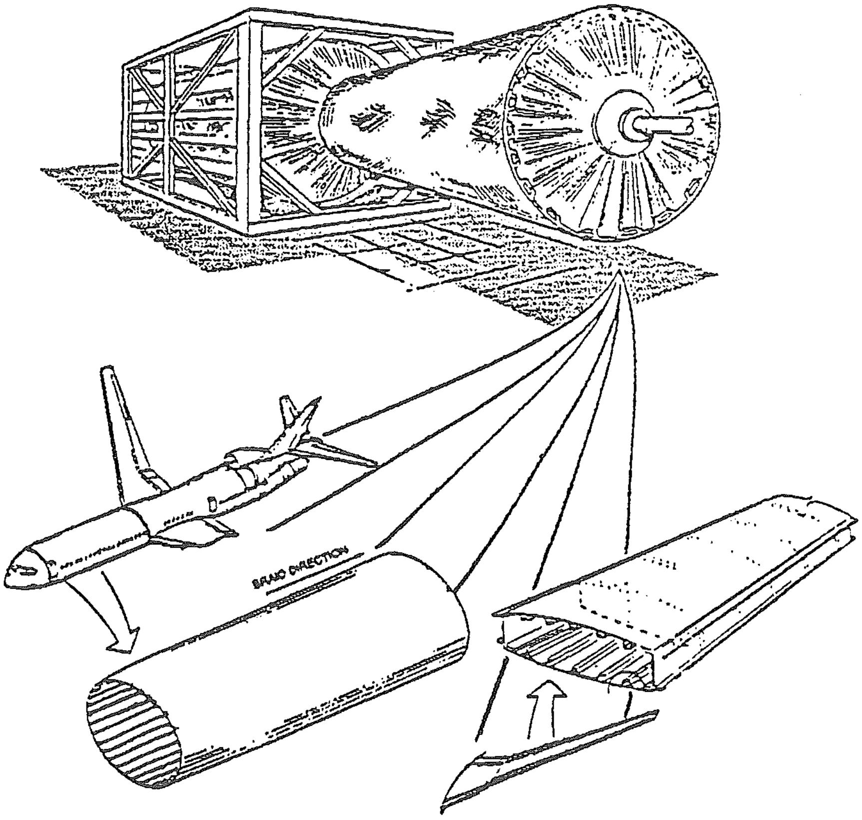


Figure 3 Artists Conception of Lower Cost Structural Components Manufacturing