$\psi = 0°$, and therefore may not be accounted for by the theory.

The number of representative coordinates and azimuth angles chosen in this example is not, of course, large enough, but the computer capacity did not permit the use of a greater number of them.

Conclusions

In this theory, the lifting-line equations of the rotor blade have been derived, through approximations as reasonable as possible, from the lifting-surface equation, which is exact within the scope of the linear theory. However, as seen from the numerical example, the effect of the distortion, especially the rolling-up, of the wake vortex sheet seems to be significant. If there exists a limitation of validity of the linear theory, this will be revealed through further comparisons between calculations by this theory and accurate experimental results.

When considered from a standpoint of the balance of the degree of approximations, this theory may possibly have unnecessarily precise portions as compared to the assumption neglecting the aforementioned nonlinear effects. It seems that further developments of the rotor theory should be directed to simplifying such portions, if they exist, and taking account of the distortion of the wake vortex sheet.

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MAY-JUNE 1967 J. AIRCRAFT VOL. 4, NO. 3

Structures Cost Effectiveness

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The principles of structures cost effectiveness are discussed, and an analytical method is presented to establish the optimum structural material/design concept that provides the best balance between weight and cost for a given vehicle. The criterion for selection of the optimum cost-weight design is dependent upon the value of weight saving applied to the vehicle under study. This value, or worth of saving weight, is derived in a sample analysis of the total systems costs associated with a fighter aircraft representative of typical current vehicles. It is shown that the optimum design for structures cost effectiveness may differ from the minimum-weight concept, and that the merit function used in this method may be applied to any structural design problem wherein weight and cost are the prominent evaluation factors. In several illustrative examples, the structures cost effectiveness approach is applied to various design areas in a typical high-aspect-ratio wing box.

Nomenclature

C_b = basic material cost, $/lb
C_i = cost of producing ith design concept
E = modulus of elasticity, psi
L = column length, in.
N_x = distributed axial load, lb/in.
$\bar{t}$ = effective thickness, in.
V, V' = vehicle tradeoff value or slope, and component cost-weight slope, respectively
W_i = structural weight of ith design concept
$\Delta C, \Delta C'$ = change in cost for vehicle and structural components, respectively
$\Delta W, \Delta W'$ = change in weight for vehicle and structural components, respectively
Φ = cost-weight merit function
η = plasticity correction factor
ϵ = efficiency factor
ρ_m = material density, lb/in.^{3}

Presented as Paper 66-505 at the AIAA 4th Aerospace Sciences Meeting, Los Angeles, Calif., June 27–29, 1966; submitted July 18, 1966. [6.03]

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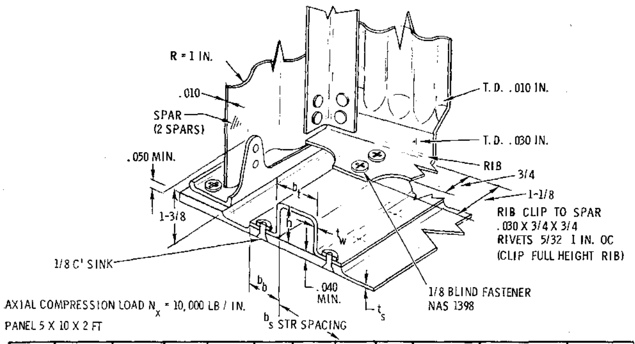
Introduction

THE ever-increasing demand for lightweight aerospace hardware, coupled with the rising costs of producing efficient structural designs, has given impetus to an effort to relate weight and costs in a rational manner. Absolute minimum-weight designs are frequently impractical to assemble, and even when producible, are often extremely costly



CONFIG NO.	MTL	RIB SPACING	b_s	t_s	t_w	h	b_t	b_b	\$ / SQ FT AT 200TH UNIT	\$ / WT (\$ / LB)	WT / SQ FT
1	Ti 8-1-1	12.	2.714	.043	.033	.798	.757	.600	131.	54.13	2.42
2	Al 7075-T6	15.	3.230	.063	.063	1.408	.982	.633	16.	5.68	2.82

Fig. 1 Producibility analysis sheet—hat stiffened column construction.

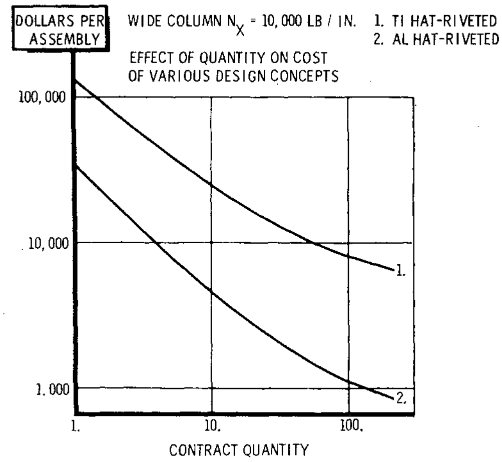


Fig. 2 Cost-quantity relationships.

to manufacture in the desired lightweight configuration. On the other hand, simple designs that are easy to fabricate and assemble are often much heavier than the minimum-weight arrangement of material. The most efficient design on the basis of both cost and weight often lies between these two extremes, and it is the intention of this presentation to illustrate how that design can be determined.

From the viewpoint of the structures engineer, the objective of any cost-weight study is to provide an efficient structural arrangement of material with an optimum balance between weight and production costs. The determination of the optimum weight-cost design requires an intermingling of many aircraft engineering disciplines: analytical and design experience, materials and producibility technology, and fabrication and assembly knowhow. The technological resources that must be employed are as follows: 1) a rational method for determining the sizes and weights of the various concepts under consideration, 2) a means for determining the costs associated with the manufacture of each of the contemplated constructions, and 3) a criterion for selecting the concept that provides the best weight-cost tradeoff. From these considerations, it is obvious that a realistic weight-cost tradeoff study must take cognizance of numerous input parameters, and evaluate the major aspects of the problem in the light of the proper criterion, to ascertain the best weight-cost design selection.

Structural Optimization and Cost Analysis

An optimum structural arrangement of material can be established for most aerospace vehicle components by judicious applications of the established principles of minimum-weight design. For compression-loaded structures, design for simultaneous mode failure in local and general instability[1,2] is one accepted approach. Design synthesis techniques that include constraining conditions are being applied in many situations.[3] Optimization methods for shear-designed members, and for components requiring specified stiffnesses, are well known throughout the industry. Most aerospace hardware-oriented companies have provided themselves with computer-programmed solutions to structural optimization problems. Methods such as those outlined in Refs. 3 and 4 provide the means for determining minimum-weight configurations for compression-loaded structures. In addition to these, a wealth of publications on most other aspects of structural design optimization is easily obtained.

The consideration of the costs associated with a given structural design provides an added dimension to the optimization analysis. A thorough analysis of all factors influencing the cost of producing a structurally efficient design is absolutely essential in the cost-conscious aerospace industry. The unique feature of a combined structural optimization/producibility cost analysis demonstrated in this presentation is the ability to systematically select that design offering the best tradeoff between weight and cost for a particular vehicle application.

The structural concept sketch and tabulated data shown in Fig. 1 are representative of the design and cost information generated in a combined optimization-producibility analysis. The structural concept shown was designed for the indicated load level by the optimum design procedures of Ref. 4. The theoretical dimensions were adjusted for producibility, and the resulting design was analyzed for manufacturing costs.[5] A typical cost-quantity relationship for these designs is shown in Fig. 2. Depending on the expected production output of each design, a realistic cost evaluation for this concept can be determined from the graph.

It should be noted that the data shown in Fig. 1 indicate two potential materials of construction for the design load level. The titanium design offers the least weight concept, at a cost (dollars per square foot at the 200th unit) considerably higher than the comparable aluminum version. The question that will be answered is which of the two designs offers the best weight-cost advantage for a given vehicle application.

Vehicle Tradeoff Value

In the discussion of aircraft weights and costs in Ref. 6, the importance of both structural weight and cost is emphasized. The data of Fig. 3 are based on a study of 22 aircraft of varying size and weight, and indicate airframe weight to be approximately 60% of the weight empty. Even more important is the ratio of structural weight to payload, which may run as high as 400%. Small variations in struc-

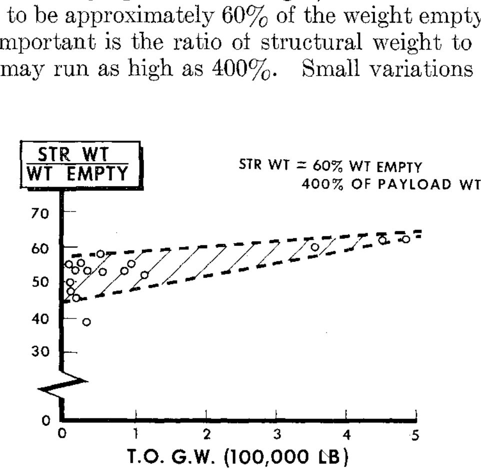


Fig. 3 Aircraft weight.

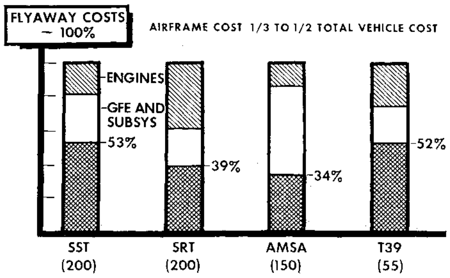


Fig. 4 Aircraft cost.

tural weight can produce large reductions in payload or range. In addition, it is seen in Fig. 4 that from one-third to one-half of the total flyaway costs, including engines and equipment, is invested in the airframe. These facts lead to the obvious conclusion that minimizing both weight and cost is desirable. However, this creates a paradoxical situation in that weight minimization efforts tend to result in escalating costs. Therefore, the point must be established beyond which further weight reduction efforts are economically unjustified.

The key to the design process that integrates and evaluates both weight and cost on an equitable basis is the value, or worth in dollars, of a pound of weight saved for a given vehicle. Weight and cost are balanced in relation to an established air vehicle system tradeoff value, expressed in dollars per pound of weight saved.

The tradeoff value is determined by varying the weight of the airframe and resizing all components to maintain the specified performance. For example, included is the change in engine size, fuel capacity, and airframe to accommodate the vehicle growth. This establishes a dollar increment in initial flyway cost, and to this must be added the variation of service life cost of fuel consumption, maintenance costs, and depreciation due to the growth factor effects. This total dollar increment divided by the initial airframe weight increment provides the resultant tradeoff value in dollars per pound of weight saved. Figure 5 illustrates the effect of weight changes both on air vehicle gross weight, including growth factor, and on total system cost in dollars. For example, consider a basic air vehicle design that weighs 100,000 lb at takeoff gross weight. If 4000 lb can be removed from the vehicle airframe, the gross weight reduces to 87,000 lb (growth factor is approximately 3). As a result of the reduction in gross weight, the over-all system cost is reduced from \$3.02 to \$2.80 billion for the initial investment and 10-yr operating period. Therefore, expenditures up to this dollar difference could be spent on airframe weight removal and result in a net dollar saving to the total program.

The total system costs can be broken down, as shown in Table 1, into costs per air vehicle. The basic design vehicle costs total to \$15.10 million per aircraft (\$3.02 billion for 200 vehicles). The basic airframe cost is \$2.6 million. For the target design, the total costs (less airframe) are \$11.57 million per air vehicle, leaving the airframe amount of \$3.53 million per vehicle for a break-even total system cost. The dollar increment available for weight reduction is found to be \$0.93 million. Therefore, with a 4000-lb reduction, the tradeoff value, or worth of weight saving, is

$$V = \Delta C/\Delta W = \$0.93 \text{ million}/4000 \text{ lb} = \$232/\text{lb} \quad (1)$$

The established tradeoff value can be graphically illustrated from the basic and target design airframe costs, as shown in Fig. 6. The line connecting the two designs establishes the maximum permissible slope in cost-weight space to reach the break-even point. It is economically not justified to exceed this slope, since spending greater dollars per pound would result in a net higher cost to the system. Spending at a slope of less than \$232/lb results in a net dollar saving to the over-all program.

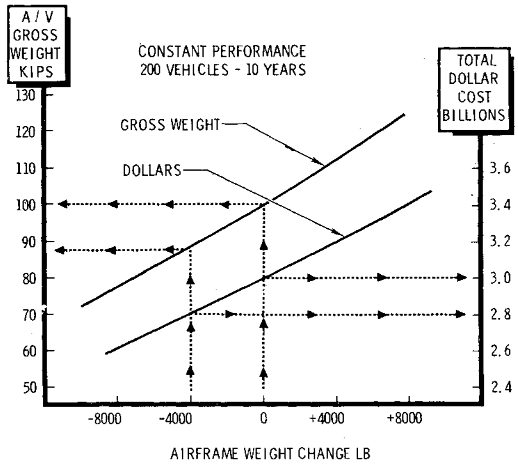


Fig. 5 Effect of airframe weight on gross weight and total cost.

Structures Cost Effectiveness

Once a worth of saving weight has been determined for a particular vehicle, the foundation has been prepared for the cost effectiveness analysis of the structural concepts. The tradeoff value of saving weight from Fig. 6 can be expressed mathematically as $\Delta C/\Delta W$, Eq. (1), where ΔC is the calculated cost difference associated with an airframe weight difference ΔW. Considering the two structural concepts previously discussed and shown in Fig. 1, Eq. (1) will be employed to decide if the lighter titanium design is economically superior to the lower-cost aluminum concept. The value V of Eq. (1) defines a maximum permissible slope in cost-weight space. The expenditure of ΔC \$ to save ΔW lb of airframe weight is considered an acceptable compromise. Transferring this postulation from the airframe to its components (using the two concepts of Fig. 1 as typical examples) results in the following expression:

$$V' = \Delta C'/\Delta W' = (C_i - C_j)/(W_j - W_i) \quad (2)$$

where the subscripts i, j, refer to the titanium and aluminum versions, respectively. Similar to Eq. (1), Eq. (2) also defines a slope in the cost-weight space pertaining to these structural concepts. The vehicle tradeoff value must be compared to the slope given by Eq. (2) to decide which of the two design concepts should be selected. It is obvious that, if the slope of the concepts, as given in Eq. (2), exceeds the maximum permissible slope in cost-weight space V, the expenditure of \$ $\Delta C'$ cannot be justified economically. For the condition

$$V'/V \leq 1.0 \quad (3)$$

the expenditure of $\Delta C'$ \$ is considered financially acceptable,

Table 1 Cost breakdown per air vehicle

Gross weight	Basic design 100,000 lb	Target design; basic–4,000 lb 87,000 lb
10-yr operating cost	8.20[a]	7.65[a]
Airframe cost	2.60	...
Engines and equipment	1.94	1.72
Research, development test, and evaluation; spares; aerospace ground equipment; etc	2.36	2.20
	15.10	11.57

Break-even airframe cost[a]: 15.10 − 11.57 = 3.53
Dollar increment[a]: 3.53 − 2.60 = 0.93 ...
Tradeoff value = \$0.93 million/4,000 lb = \$232/lb wt saved

[a] Values are in millions of dollars.

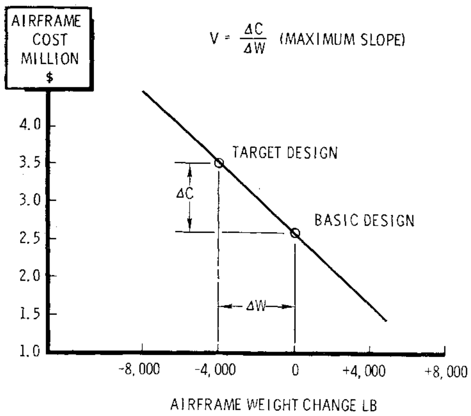


Fig. 6 Tradeoff value represented graphically.

and becomes increasingly worthwhile as Eq. (3) regresses from unity.

From these considerations of weight, cost, and the vehicle tradeoff value, the weight-cost effectiveness merit function was evolved. From the mathematical relationships of Eqs. (2) and (3), it can be stated that, for any number of concepts designed for a given structural requirement, the optimum weight-cost design is that one which minimizes the expression

$$\Phi = W_i + C_i/V \tag{4}$$

Equation (4) is the merit function for determining which of several potential designs offers the best structural weight and production cost relationship for a given vehicle requirement. Expressed in this simple form, the weight-cost merit function places the most emphasis on the weight of a given concept, but includes a fair appraisal of the cost influence in relation to the established worth of weight saving. Since it is seldom that one encounters a minimum-weight design for the least cost among a group of candidate concepts, the weight-cost merit function provides the necessary criterion for the selection of the design that optimizes both weight and cost.

Considering the weight and cost data for the hat-stiffened concepts shown in Fig. 1, the weight-cost merit function will be employed to answer the question of which design is the best selection on the basis of structural cost effectiveness. For this design example, it is assumed that these aluminum and titanium concepts are to be employed in the vehicle described in Fig. 6. Using the weight and cost values from Fig. 1, the graphs of Fig. 7 were constructed for various values of weight saving. Plotting Φ, the weight-cost merit function [Eq. (4)] vs V, the value of weight savings, illustrates the variation of the merit function for each design concept. At a value V = \$232/lb, the aluminum design is seen to be slightly more efficient (approximately 3%) on a weight-cost basis than the titanium version. (Recall that the minimum merit function number is the best choice.) Therefore, the conclusion would be to adopt the aluminum design for this vehicle. Although the titanium design is lighter than the aluminum concept, the graph of Fig. 7 illustrates that the weight difference cannot be economically justified unless the vehicle tradeoff value is in excess of \$290/lb. Note that the graph of Fig. 7 allows for any subsequent variations in the assigned value of weight savings to be applied to this design evaluation. Should the value of weight savings change for some reason, the graph can still be employed if the same designs are still in contention.

It should be evident from Fig. 7 that, as the value of weight savings increases, the merit function approaches asymptotically the basic weight of each concept. In other words, when weight minimization tends to become all-important, the merit function reflects the minimum-weight design as the obvious solution, as it should. Also, when cost considerations are emphasized, the merit function fairly evaluates both weight

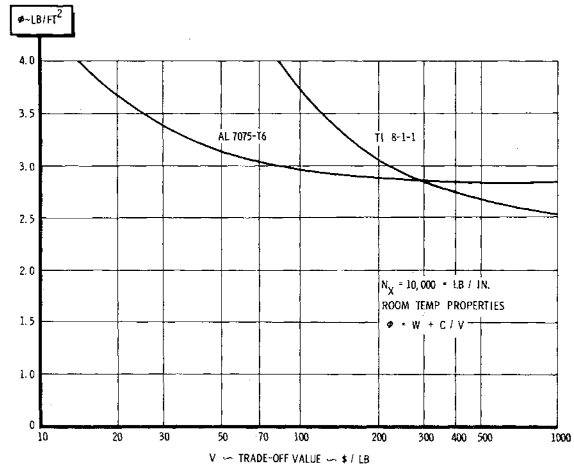


Fig. 7 Hat stiffened panels—weight/cost effectiveness.

and cost of each concept, in relation to the value of saving weight. Therefore, the least weight concept (titanium) is indicated to be the best cost-weight choice for high V numbers, and the least cost concept (aluminum) is indicated for low V numbers.

Additional Examples

The preceding illustration was but one of the many possible applications of the principles of structural cost effectiveness. In order to explore additional possibilities for use of this technique, consider the various components of an aircraft wing.

Compression Cover

The compression cover of a typical high-aspect-ratio wing box can be analyzed for weight-cost effectiveness using a combined optimization and producibility approach. Consider the wing box structure shown in Fig. 8. The inboard portion of the box upper surface will be analyzed for a design ultimate axial load level of 8000 lb/in. A Z-stiffened cover has been selected for the load-carrying requirement, with a fixed rib support spacing of 20 in. An efficiency equation of the form

$$N_x/L = \epsilon\eta E(\bar{t}/L)^2 \tag{5}$$

is employed to determine the effective thickness ($\bar{t}$) and associated design dimensions of the cross section. By systematically varying the efficiency factor (ϵ) from maximum efficiency to other off-optimum values, a variation in cover panel weight and spacing of the Z stringers results. This variation in weight and stringer spacing is essential in a weight-cost analysis. Minimizing the number of pieces and lines of attachment is a firm guideline for cost reductions. By increasing the spacing of the Z stringers, the total number of details and lines of attachment are reduced, thereby reducing the cost of manufacturing and assembly. The perti-

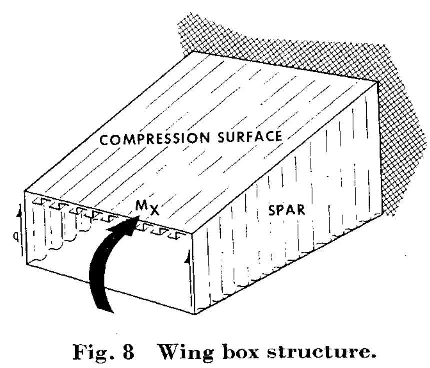


Fig. 8 Wing box structure.

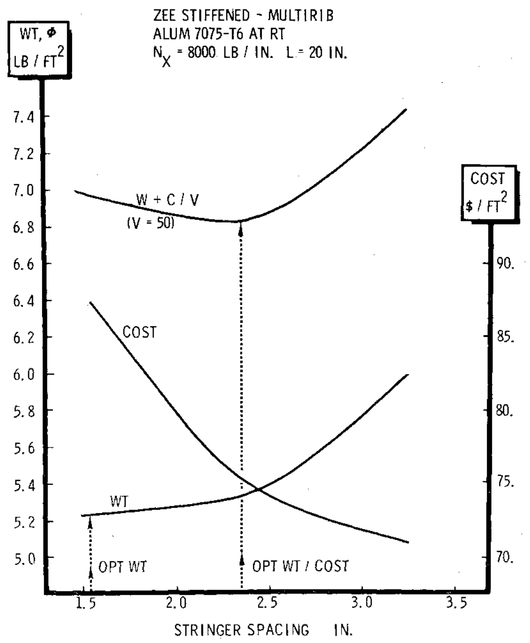


Fig. 9 Optimum weight/cost stringer spacing.

nent dimensional, weight, and cost data resulting from this analysis are shown in Table 2.

Note the effect of increased stringer spacing driving costs downward with small variations in the weight penalty. Considering the trends of increasing weight and decreasing costs, shown in Table 2, intuitively suggests that a tradeoff possibility exists. The best design on the basis of weight-cost effectiveness can be determined by the merit function. Dividing the cost of each design by the tradeoff value (assumed at \$50/lb for this example) allows the computation of the merit function Φ, given by Eq. (4). By performing this summation at discrete values of the variable b_s, a "bucket" curve is produced which indicates the optimum stringer spacing for the particular vehicle under study (see Fig. 9). A discrete "bucket" curve can be plotted for any desired tradeoff value. This calculation is mathematically equivalent to a solution of the expression

$$d\Phi/dx_i = 0 \tag{6}$$

which is the weight-cost counterpart to a familiar structural weight optimization equation. Note that the least weight design is not indicated to be the best choice for structural cost effectiveness in this example. As in the previous example, a graph of the merit function vs value could also have been

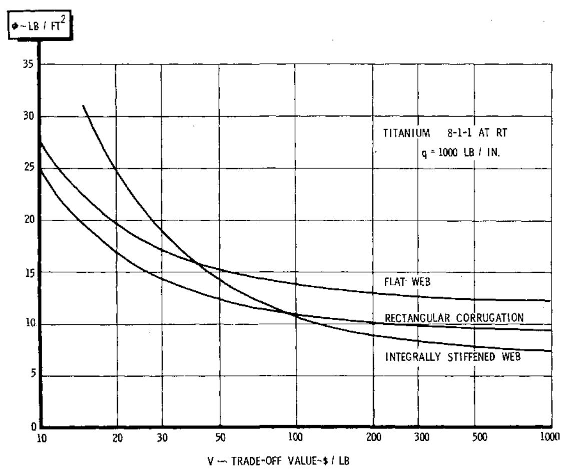


Fig. 10 Shear web designs—weight/cost effectiveness.

Table 2 Z-stiffened, multirib, Alum 7075-T6 at room temperature

Configuration	Stringer spacing	Weight, psf	Cost, \$/ft², 200th unit
1	1.538	5.23	87.51
2	1.764	5.25	83.79
3	2.049	5.28	78.90
4	2.351	5.33	75.24
5	2.770	5.58	72.87
6	3.217	5.97	71.21

constructed for this case to illustrate the optimum design choice for any assigned worth of saving weight.

The cost analyses employed in these examples of structures cost effectiveness include all known cost factors, from the basic material stock to the final assembled product. Material costs that are evaluated include the cost of purchasing the required amount of structural material, and an allowance for possible rework or rejection dispositions. Labor and burden costs are evaluated and are based upon corporate-wide labor standards. Established production learning curves are used to evaluate the reduction in labor costs due to improved production control and learning with increased quantities. Tooling costs are based upon the quantity requirements in relation to the established production rate for the assembled product.

For each material/design concept, a step-by-step cost analysis is performed on each item contributing to the completed product. For example, the face sheet detail of the preceding Z-stiffened construction was evaluated for such cost items as purchase of the basic sheet, drilling, chem-milling, trimming, and deburring. The data generated included such items as material cost, setup cost, run cost, tooling cost, cumulative cost, and cost per pound. The information thus generated for this face sheet detail is then summarized by computing the total material costs, tooling costs, and fabrication costs of the individual operations involved.

In a sequence of 12 operations on the Z stringers, the following steps were evaluated: shearing the sheet stock; deburring, numbering, and folding the formed zees; checking and straightening each part; cleaning and finishing, and heat processing. The cost data generated were exactly the same as for the facing sheet detail: material, setup, run, tooling and cumulative costs, plus cost per pound. These data were then summarized as previously noted.

In this manner, each detail of each design concept is thoroughly analyzed for costs, in order to assure that the subsequent weight-cost evaluation is based upon meaningful data.

Spars

Several design possibilities for shear webs with varying weight and cost figures can be examined to determine an optimum weight-cost concept for the subject wing box. For this example, a design load level q = 1000 lb/in. and titanium 8-1-1 material were assumed.[7] Three types of shear webs

Table 3 Shear web designs, Titanium 8-1-1 at room temperature, q = 1000 lb/in.[a]

Design concept	Web, t	Weight, psf	Cost, \$ft², 200th unit
Flat web	0.452	12.33	151.42
Integrally stiffened web	0.263	7.23	359.43
Rectangular corrugation web	0.262	9.46	153.35

[a] Weight and cost data include spar caps and attachment to upper and lower wing surfaces; panels 20 by 100 in.

Table 4 Fatigue cost-weight evaluation[a]

Material	F_{tu}, ksi	% F_{tu}	T, in.	Weight, lb	Cost C_b, \$/lb
Al 2024-T3	68	29	0.102	1.47	0.60
Al 7075-T6	79	20	0.127	1.83	0.72
Ti 6-4 (STA)	160	21	0.060	1.38	15.00
PH15-7 (RH1050)	200	24	0.042	1.68	2.50
4130 steel	125	32	0.050	2.16	1.00

[a] Weight and cost data are for flat sheets and include costs of any trea ments required to attain desired strength levels. Number of cycles require 10^5; maximum (1g) load: 2000 lb/in.; room temperature properties: K_T = 2.50, R = − 0.5.

were considered: flat web, integrally stiffened web, and rectangular corrugations. The weight and cost data associated with each concept are as shown in Table 3. The least-weight concept is shown to be the integrally stiffened web construction, but is also the most expensive of the three designs. The rectangular corrugation concept is competitive from a cost standpoint. Applying the weight-cost effectiveness yardstick to this problem results in the graph of Fig. 10. Employing the tradeoff value of \$232/lb, the least-weight concept (integrally stiffened) is the indicated optimum design. The rectangular corrugation is shown to be most effective below a value of \$95/lb, and the least cost concept appears as a third-rated design. The lower cost of the flat web concept could not offset the superior weight-cost relationship of the rectangular corrugation throughout the entire range of tradeoff values investigated. In this instance, the least weight concept proved to be the optimum design choice considering both weight and cost.

Tension Cover

In this example, a demonstration of the weight-cost analysis in a fatigue design area is presented. It is acknowledged beforehand that some liberties have been taken to simplify a design process that is normally complex. Only flat sheets are considered in both the weights and costs of the assumed materials. Normally, a stiffening system would be required for reversed wing bending conditions, fail-safe design philosophies, and the like, which would distribute the effective cover material between skin and stringers. However, it was assumed that the fatigue design conditions serve to establish an effective thickness requirement, which could subsequently be distributed to satisfy these other criteria. Therefore, for this example, the weight and cost data are relative to an effective thickness requirement only. The fatigue design conditions are as noted in Table 4, which lists the pertinent dimensions and costs for the five materials considered.

The cost associated with each material includes the basic purchase price plus any subsequent treatment required to produce the desired strength levels. For this example, the weight-cost merit function is given as

$$\Phi = 144\,\rho_m \bar{t}(1 + C_b/V) \tag{7}$$

The merit function has been plotted vs tradeoff value in Fig. 11. The low-cost aluminum 2024-T3 is shown to be a definite weight-cost optimum throughout the value range up to a \$250/lb tradeoff. The least weight material, titanium 6-4 (STA), becomes only slightly more effective beyond this point. It is also interesting to note that PH15-7 steel runs a close third, excelling aluminum 7075-T6 throughout most of the value range shown. Although this example presents a greatly simplified approach to a fatigue design situation, it is felt that the results shown in Fig. 11 present some illuminating insight on the influence of costs and weights which is worthy of consideration.

Another aspect associated with this example is that of basic material costs. Although the titanium material costs 25

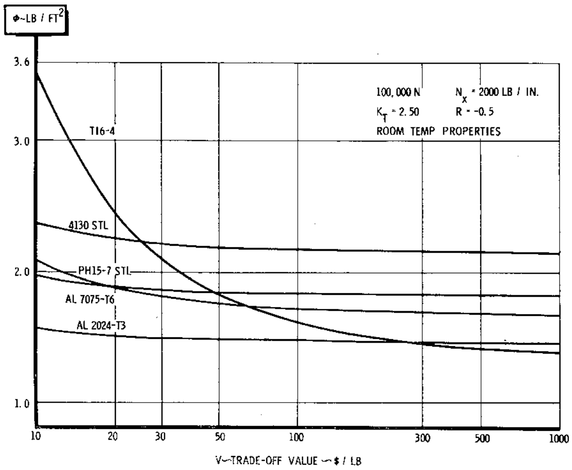


Fig. 11 Tension fatigue designs—weight/cost effectiveness.

times the least expensive aluminum, its weight advantage automatically provides a qualifying edge when the worth of saving weight becomes great enough. In many instances such as this, the undue emphasis placed on basic material costs is largely unjustified based on realistic appraisals.

Conclusions

A rational approach to the selection of structural design concepts has been presented which considers both weight and cost in its evaluation of the optimum design. A weight-cost merit function has been introduced which is simple and direct in application to various structural cost effectiveness design problems. The merit function employs a tradeoff factor that is the dollar value assigned to weight saved on a given vehicle. This value, or worth of saving weight, provides the key to the determination of the optimum design on the basis of weight and cost. It has been shown that the optimum weight-cost design may differ from the least weight design, depending on the tradeoff value assigned to the problem. It is believed that the merit function approach to structural cost effectiveness in aerospace structural design will provide a useful tool for the selection of optimum structural concepts. The greatest benefit can be derived by application of the structural cost effectiveness principles in the preliminary design stages. Furthermore, this weight-cost effectiveness approach should prove advantageous for any design situation in which weight and cost are the principal considerations.

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