Structural Guidelines for Materials Development: Some Vehicle Performance and Design Generalizations

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Starting with the generalization that the function of a vehicle is efficient transportation of a given payload over a given distance, the structural weight fraction has been identified as the factor most sensitive to structures and materials improvement. Furthermore, the value of structural weight saving over the life of the vehicle can be large and thus relatively large costs can be expended in such endeavors. Analysis of the factors comprising the structural weight fraction has led to the important generalization that the structural design of the vehicle or its major components is characterized by rather narrow ranges of the maximum design index. It is this factor which dictates the specific improvements in materials (or structures) that can result in a meaningful reduction of the structural weight fraction.

Introduction

ANY attempt to define structural guidelines for the development of improved material properties and to assess the real significance of projected improvements is necessarily based upon an understanding of current and projected vehicle requirements. In the past, material improvement requirements have been based upon rather detailed analysis of a large number of current and advanced vehicle concepts; from the analysis of many "trees," some general impressions of how to improve the "forest" have been projected.

In the following analysis, we will attempt to survey the "forest" directly without direct reference to its individual members by establishing some important and underlying generalizations concerning vehicle performance and design. It will be shown that many vehicle types and sizes tend to conform to certain well-established laws that can be used in a rational manner to establish the significance of improvements in selected material properties.

Vehicle Performance Generalizations

As a basic generalization, it can be stated that the basic vehicle mission is to transport a given payload over a given distance, whether the purpose be commercial or military in nature. Depending upon the purpose, speed can be an important consideration.

Generalizations Concerning Speed

An extremely interesting and important generalization concerning the speed of all types of vehicles in terms of the propulsive power per unit weight transported (specific power) was formulated by Gabrielli and von Karman[1] in 1950. For a given vehicle type, they postulated that the minimum specific power

> . . . is determined by the physical laws of the resistance of the medium, the efficiency of the method of propulsion, the unit weight and fuel consumption of the particular type of power plant, and many other factors. Nevertheless, it appears that if one throws all data together, a general trend, almost a kind of universal law, can be found for the power required per unit gross weight of the vehicle as a function of maximum speed.

This pioneering effort served to indicate that it is possible to develop important generalizations concerning vehicles and to promote work by others in attempting to understand the physical principles underlying such generalizations. Davidson[2] was specifically interested in surface ships and by utilizing and further analyzing the results of Ref. 1 concluded that there were several methods for improving performance of conventional ship forms. This indicated that the Gabrielli-von Karman law in no sense constituted an upper bound or limit to vehicle performance and that performance improvements could be expected as the state-of-the-art progressed.

In another study, the concepts of Ref. 1 have been used, as reported by Mandel,[3] in an entirely different sense to evaluate the relative transport efficiency and potential of various types of novel, unconventional, hull forms. By comparing the estimated performance of the novel forms with that of more conventional vehicles as represented by the Gabrielli-von Karman law, important and significant conclusions were deduced as to the transport potential of the novel forms.

More recently, Bisplinghoff,[4] using an alternate form of presentation of the essential results of Ref. 1, indicated the state-of-the-art improvements in vehicle performance since 1950 and provided an estimate of the potential efficiency of Mach 3 supersonic transports as well as projected Mach 6 hypersonic transports. These results are presented in Fig. 1 in terms of effective lift/drag $(L/D)_e$ ratio (equivalent to weight/thrust ratio) as a function of vehicle speed.

An important generalization which seems to emerge from Fig. 1 is that, for a new type of vehicle to be competitive with more established types in terms of transport efficiency, the index $V(L/D)_e$ characterizing the vehicle should correspond to the current state-of-the-art. Conversely, the inadequacy of current V/STOL aircraft, hydrofoil boats, GEMs, and helicopters with respect to this index is clear evidence of their poor transport efficiency, a fact currently recognized and one which restricts such vehicles to special purpose missions.

Generalizations Concerning Range

The results given in Fig. 1 essentially represent empirical generalizations concerning speed and, therefore, it is highly desirable to establish a rational physical basis for these results. For this purpose now, we shall consider the Breguet range equation which represents a fundamental physical generalization concerning the range of various types of vehicles. Examination of the factors comprising this equation will provide a physical basis for the Gabrielli-von Karman generaliza-

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tion as well as indicating those factors sensitive to materials and structures improvements.

The Breguet relation can be written in a variety of equivalent forms,[5-7] most of which shall be discussed subsequently. For our purposes, the following is convenient:

$$R = \eta_a \eta_p \ln(W_0/W_t) \tag{1}$$

where

R = range
η_a = measure of aerodynamic or hydrodynamic efficiency of the vehicle
η_p = measure of propulsion system
W_0 = initial vehicle weight
W_t = terminal vehicle weight

The aerodynamic or hydrodynamic efficiency is essentially measured by the maximum effective $(L/D)_e$ of the vehicle. In alternate forms,

$$\eta_a = (L/D)_e = (W/T)_e \tag{2}$$

Methods of determining $(L/D)_e$ as well as typical values are available for ships,[3] aircraft,[5] ballistic,[6] and hypersonic[7] vehicles. This factor depends completely upon the aerodynamic or hydrodynamic shape of the vehicle and is thus not influenced by structures and materials.

In its most fundamental form, Rutowski[5] has shown that the propulsive system efficiency is

$$\eta_p = \eta_t H_c \tag{3}$$

In Eq. (3), H_c is the heat content or chemical energy contained in the fuel and is obviously independent of structures and materials considerations. For hydrocarbon fuels, H_c = 18,800 Btu/lb, which also can be expressed more conveniently for the purposes of Eq. (1) as H_c = 2400 naut miles (by use of the conversion factor 1 Btu = 778.3 ft-lb).

The term η_t in Eq. (3) is selected as a representation of the thermal efficiency of the propulsion system in converting the chemical energy of the fuel into propulsive energy. A representative value for efficient internal combustion engines[5] is $\eta_t = 0.3$. Inasmuch as η_t represents the thermal efficiency of the propulsion cycle, it is independent of structures but does depend upon materials considerations. However, it is quite apparent that whereas the high temperature capabilities of materials do influence η_t, significant progress in achieving relatively high efficiencies in current engines has resulted from improvements in the basic propulsion cycle rather than from materials.[8] Thus, as a first approximation, it appears reasonable to conclude that the η_p as well as η_a terms of Eq.

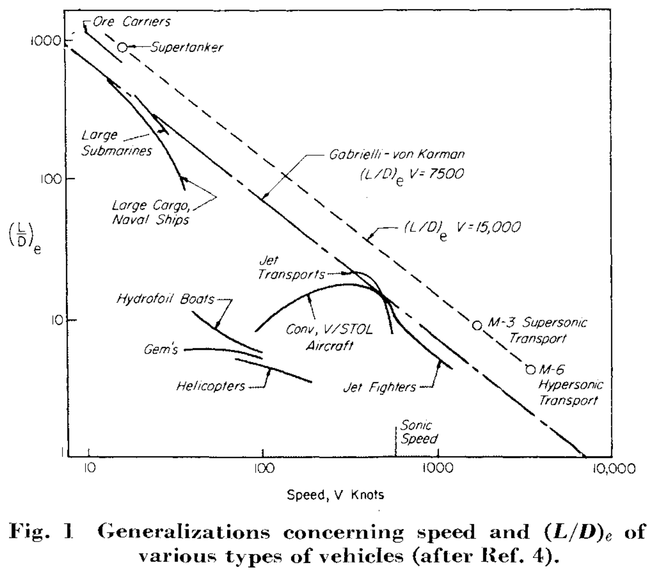

Fig. 1 Generalizations concerning speed and $(L/D)_e$ of various types of vehicles (after Ref. 4).

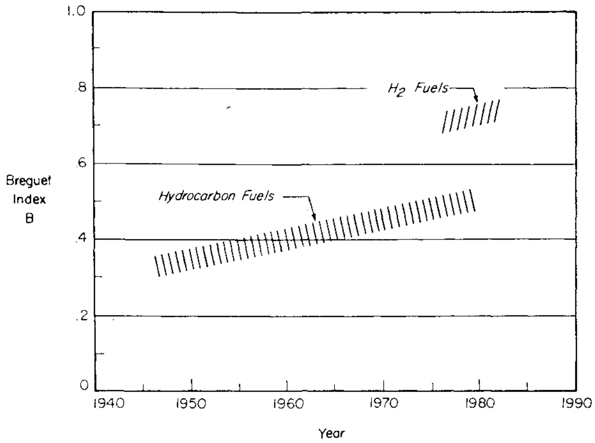

Fig. 2 Best state-of-the-art Breguet index values achieved in the past, and projected estimate into the future for vehicles utilizing different types of fuels.

(1) are essentially independent of structures and materials considerations.

Although the form of η_p given by Eq. (3) is fundamental, there are alternate relations that are commonly used for performance calculation purposes;

$$\eta_p = I_{sp}V = V/\text{tsfc} \tag{4}$$

From Eq. (4), it follows that the specific impulse $I_{sp} = (\text{tsfc})^{-1}$, the thrust specific fuel consumption (lb fuel/unit time-lb thrust). For efficient engines powered by hydrocarbon fuels, the specific impulse can be approximated by a constant.

We can now return to one of our original objectives in analyzing the Breguet range equation and observe that, within a constant represented by I_{sp}, values of the Gabrielli-von Karman index $(L/D)_eV$ characterizing hydrocarbon fueled vehicles, and the product $\eta_a\eta_p$ appearing in Eq. (1) are equivalent;

$$\eta_a \eta_p = [(L/D)_e V] I_{sp} \tag{5}$$

Having established this correspondence, we will henceforth utilize Eq. (1) in the following nondimensional form:

$$\bar{R} = R/C = B \ln(W_0/W_t) \tag{6}$$

where

C = circumference of earth = 21,600 naut miles
B = Breguet index, $B = \eta_a\eta_p/C = (L/D)_e I_{sp} V/C$

We can note that state-of-the-art progress in aerodynamic, hydrodynamic, or propulsive efficiencies will be reflected by increases in the nondimensional Breguet index B. Progress since 1950 as well as projections for hydrocarbon and hydrogen fuel vehicles based upon data of Refs. 4 and 7 are shown in Fig. 2.

Weight Ratios

The one factor remaining in Eqs. (1) or (6) that has not been discussed thus far is the weight ratio W_t/W_0. In alternate forms,

$$W_t/W_0 = (W_l/W_g) + (W_e/W_g) = 1 - (W_f/W_g) \tag{7}$$

where

W_l = payload
W_e = empty weight of vehicle
W_f = fuel weight
W_g = gross weight of vehicle

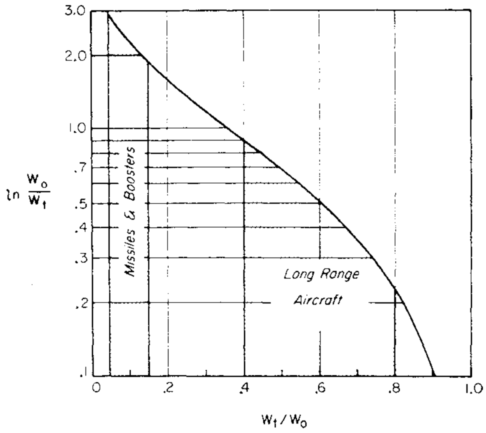

Fig. 3 Variation of weight ratio for different types of vehicles.

and

$$W_g = W_e + W_l + W_f \tag{8}$$

The weight ratio W_t/W_0 can vary widely for various types of vehicles, as indicated in Fig. 3. Because of the form in which the weight ratio appears in Eq. (6), it can be observed that it can have a profound effect upon range for a given value of B.

From a materials and structures viewpoint, the payload (W_l) represents a given design condition and is therefore independent of such considerations. On the other hand, the empty weight (W_e) is directly dependent upon structures and materials efficiencies since

$$W_e = W_s + W_p + W_{eq} \tag{9}$$

where

W_s = structural weight, $W_s \simeq W_e/2$
W_p = dry propulsion weight, $W_p \simeq W_e/4$
W_{eq} = equipment weight, $W_{eq} \simeq W_e/4$

Based upon available data on aircraft,[9, 10] missiles, and ships,[3, 4] some generalizations concerning weight fractions for a wide variety of vehicle types and sizes can be obtained as indicated in Fig. 4. Typically, the structures weight comprises one half of the empty weight of aircraft, missiles, and boosters. Thus, it can be expected that the greatest benefits of improvements in structures and materials will be realized in the airframe. The proportionate benefits of such improvements to the propulsion system or equipment will necessarily be less, although still important.

Growth Factors

In the preliminary design of a vehicle to transport a given payload a given distance, any reduction in structures weight resulting from materials or structures improvements will require a smaller propulsion system and probably a smaller weight of equipment. Thus, the empty weight is significantly reduced thereby requiring less fuel for the same performance with a consequent substantial reduction in the gross weight of the vehicle. This "snowballing" effect is called the growth factor[11] and has been defined as the change in gross weight due to a change in empty weight or its components.

Mathematically, on the basis of empty weight, the growth factor

$$G_e = \partial W_g/\partial W_e \tag{10}$$

From Eqs. (6) and (7), however,

$$W_g = (W_l + W_e)e^{\bar{R}/B} \tag{11}$$

Since the payload (W_l) is fixed, it follows that the growth factor based upon the empty weight

$$G_e = \partial W_g/\partial W_e = e^{\bar{R}/B} \tag{12}$$

The growth factor given by Eq. (12) essentially reflects the change in gross weight resulting from a change in empty weight, as well as the consequent change in fuel weight requirements for the specified performance.

The growth of gross weight as a function of W_e/W_l is shown in Fig. 5 for transport aircraft based upon the Breguet indices shown in Fig. 2. Also shown are the characteristics of current long-range aircraft in terms of typical values of W_e/W_l. It can be observed that the influence of the empty weight upon the gross weight is most profound, a reflection of the vital role played by the efficiency of structures and materials.

A more direct representation of the significance of a change in structures weight resulting from an improvement in the efficiency of structures and materials can be obtained by utilizing a growth factor based upon structures weight, rather than empty weight. The structural growth factor can be defined as

$$G_s = \partial W_g/\partial W_s \tag{13}$$

By utilizing Eq. (11) and replacing W_e by Eq. (9),

$$G_s = \left(1 + \frac{\partial W_p}{\partial W_s} + \frac{\partial W_{eq}}{\partial W_s}\right) e^{\bar{R}/B} \tag{14}$$

The derivatives appearing in Eq. (14) must be evaluated for a particular vehicle. However, if it is assumed that each derivative has a value of $\frac{1}{2}$, which seems likely on the basis of the data given following Eq. (9), then as an approximation

$$G_s \simeq 2G_e \tag{15}$$

Growth factors based upon propulsion or equipment weight can be similarly defined and they would be correspondingly larger.

Value of Structures Weight Saving

The value of a pound of empty weight or structures weight saved in the initial design can be substantial when considered over the lifetime of the vehicle. Values considerably over \$300/lb have been indicated for supersonic transports[12–14] and figures as high as \$1000/lb have been quoted for high-

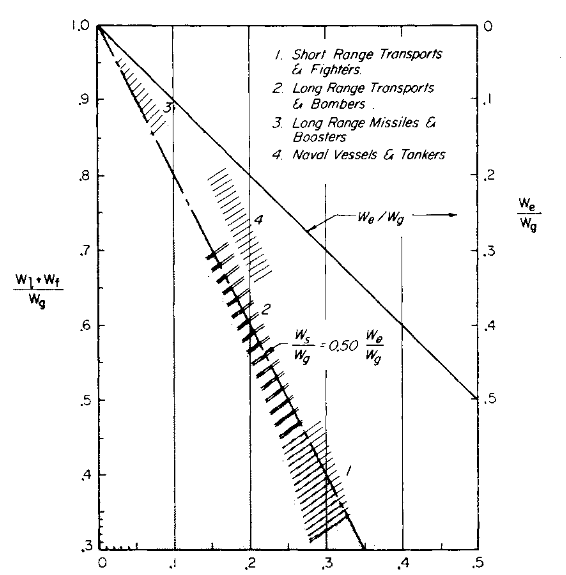

Fig. 4 Weight ratio of different types of vehicles as a function of the structural weight ratio.

performance fighter aircraft. These numbers indicate that the added expense of using more sophisticated structures concepts as well as advanced materials and fabrication approaches must be seriously considered and evaluated. Over-all system cost effectiveness can be significantly influenced by appropriate weight and cost tradeoffs.

The value of weight saving is associated with the generalized vehicle performance characteristics discussed previously and can be directly related to the vehicle gross weight. For example, the weight and cost of fuel saved over the lifetime of a transport resulting from a reduction in empty weight can be directly calculated from Eqs. (11) and (12). Less direct methods can be established to determine the reduction in size and cost of terminal facilities and handling equipment associated with aircraft and missiles of reduced gross weight.

In the following, an approximate method of analysis suggested by Childers[13] will be used to establish the value of structural weight saving. This analysis is based on fuel costs only and does not include the costs savings in terminal facilities or other areas. For each flight of a vehicle designed to carry a specified payload (W_l) over a given distance (R), the value of a pound of empty weight saved (v_e) can be evaluated in terms of the fuel weight saved (W_f) and the cost per pound of fuel (c_f);

$$v_e = c_f(\partial W_f/\partial W_e) \tag{16}$$

If n is the total number of flights during the lifetime (L) of the airplane, then

$$v_e = nc_f(\partial W_f/\partial W_e) \tag{17}$$

where $n = VL/R$.

From Eq. (8), and noting that W_l is fixed,

$$\partial W_f/\partial W_e = (\partial W_g/\partial W_e) - 1 \tag{18}$$

However, $\partial W_g/\partial W_e$ is the empty weight growth factor given by Eq. (12). Thus, Eq. (18) can be written as

$$\partial W_f/\partial W_e = G_e - 1 = e^{R/B} - 1 \tag{19}$$

On the basis of empty weight saved, Eq. (17) becomes

$$v_e = nc_f(e^{\bar{R}/B} - 1) \tag{20}$$

The value of a pound of structures weight rather than empty weight can be determined in a similar manner by use of Eqs. (13–15). In this case, it is found that

$$v_s \simeq nc_f 2(e^{\bar{R}/B} - 1) \tag{21}$$

By using a value[13] of c_f = \$0.028/lb, and assuming the following for a supersonic transport, V = 1800 knots, R = 4000 naut miles, L = 30,000 hr, and a Breguet index B = 0.45, it is found from Eq. (21) that $v_s \simeq$ \$380/lb. This value checks quite nicely with those previously quoted.

Structural Design Generalizations

The preceding material has established some significant generalizations concerning vehicle performance in terms of payload, range, and speed. It has also served to identify those factors in the over-all vehicle performance which are directly affected by the efficiencies of structures and materials. Furthermore, the sensitivity of gross weight to these factors was established quantitatively in terms of growth factor and value of weight saving.

As a good first approximation, the structures weight fraction W_s/W_g has been identified as the major contributor to vehicle performance in terms of structures and materials. Therefore, we will focus attention on this weight fraction for the purpose of developing some significant structural design generalizations.

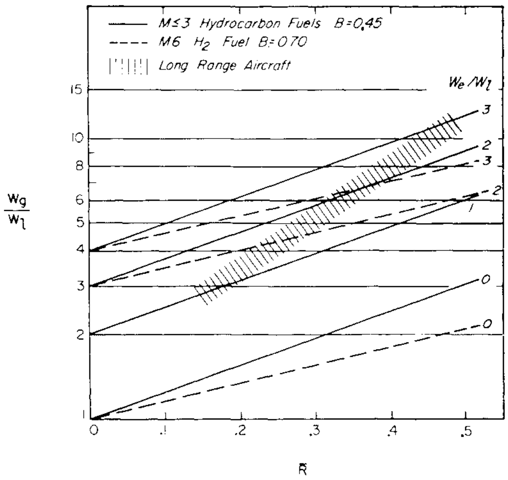

Fig. 5 Growth of gross weight as a function of R and W_e/W_l.

Structural Weight Fraction

As a basic generalization, we can write the structural weight fraction in the following forms:

$$\frac{W_s}{W_g} = \frac{\bar{\rho}_s V_s}{\bar{\rho}_g V_g} = \frac{\bar{\rho}_s \bar{t}_s A_g}{\bar{\rho}_g V_g} \tag{22}$$

where

$\bar{\rho}_s$ = average structural density
$\bar{\rho}_g$ = average gross vehicle density
V_s = volume of structural material
V_g = gross vehicle volume
$\bar{t}_s$ = average thickness of structural material
A_g = external vehicle surface area (wetted area)

Since the average gross vehicle density depends upon all items comprising the gross weight and volume, it is more convenient to deal with the structural density defined as

$$\phi_s = W_s/V_g = \bar{\rho}_s \bar{t}_s (A_g/V_g) = \bar{\rho}_s \Sigma \tag{23}$$

where Σ = solidity, ratio of volume of structural material to the enclosed volume.

The influence of structures and materials upon the various terms comprising Eq. (23) becomes immediately apparent. There is a direct effect upon $\bar{\rho}_s$ and $\bar{t}_s$ but no effect upon A_g/V_g, which is strictly a shape factor. This factor characterizes the vehicle configuration which is established by the performance requirements of the vehicle payload, range and speed. It is governed by the efficient aerodynamic or hydrodynamic design of the vehicle as represented by $(L/D)_e$ in Eq. (2).

The term $\bar{t}_s$ in Eq. (23) represents the average thickness of structural material within the external configuration of the vehicle required to satisfy the external loads and design environment as well as aeroelastic stiffness requirements. It includes the skin or plating, stiffening systems, and internal stabilizing structure. In a general manner, we can relate t_s and the external loads characterizing the vehicle by

$$\bar{t}_s = \bar{N}/\bar{\sigma} = k_s N_{\max}/\sigma_{\max} \tag{24}$$

where

$\bar{N}$ = average loading (lb/in.) produced by external loads
$\bar{\sigma}$ = average stress level (psi)
k_s = shape factor, $0 < k_s \leq 1$
$N_{\max}$ = maximum loading produced by external loads
$\sigma_{\max}$ = maximum stress level

Equation (24) is given in terms of both average and maximum loadings and stresses which differ by a factor k_s which

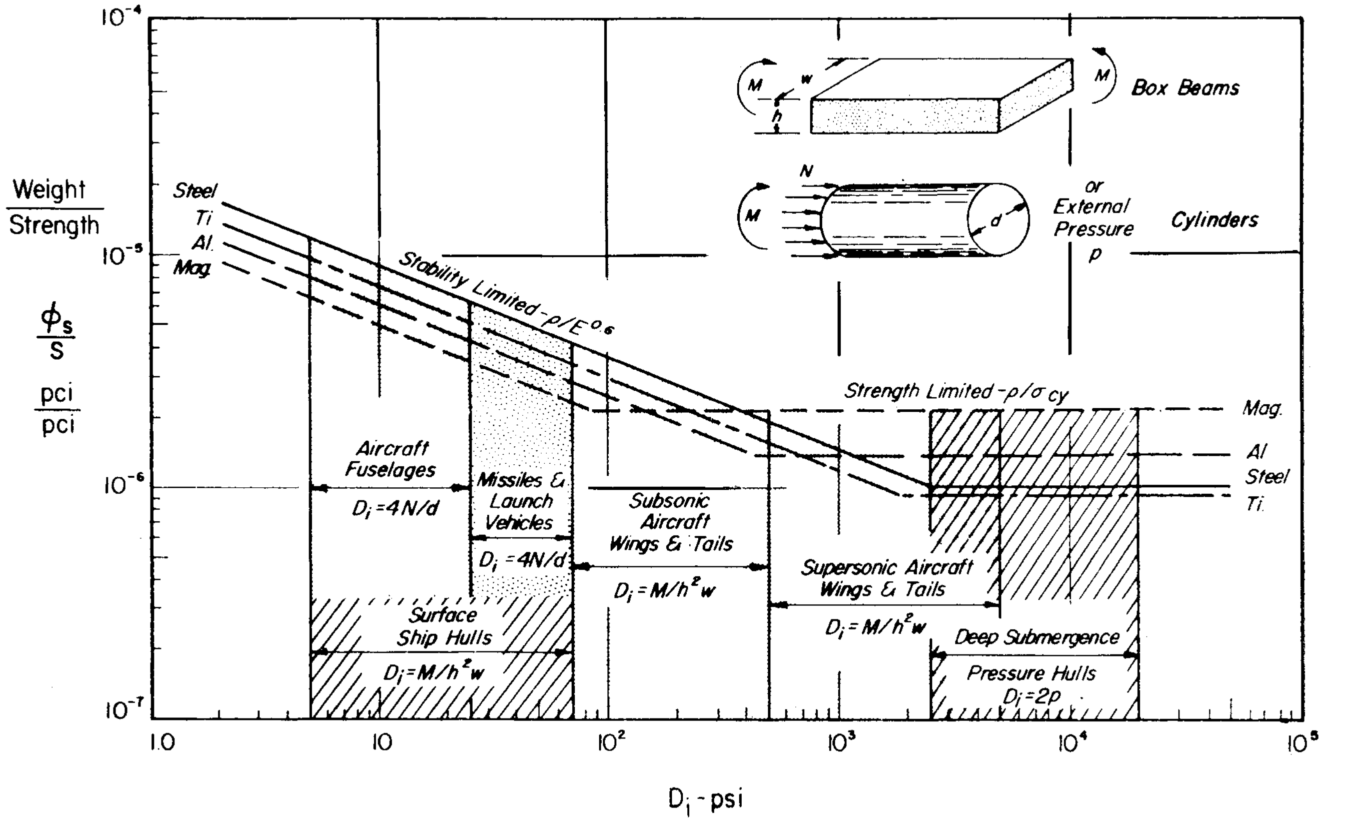

Fig. 6 Comparative efficiencies of various materials in stiffened box beam and cylinder applications. The D_i ranges shown for the various vehicle types are maximum values.

depends only upon the configuration of the vehicle. For our purposes, it will be more meaningful to consider N_{max} as characterizing the vehicle and therefore we shall utilize Eq. (24) in its second form. By substituting Eq. (24) into (23), we obtain

$$\phi_s = \frac{W_s}{V_g} = \frac{\bar{\rho}_s}{\sigma_{max}}\left(\frac{N_{max}k_sA_g}{V_g}\right) = \frac{\bar{\rho}_s}{\sigma_{max}} D_s \tag{25}$$

Equation (25) is in a particularly useful form since it relates the structural weight fraction with the external design conditions of maximum loading and configuration represented by the structural design index $D_s = (N_{max}k_sA_g/V_g)$. It also identifies the influence of structures and materials in terms of a weight/strength parameter $\bar{\rho}_s/\sigma_{max}$. Here $\bar{\rho}_s$ obviously depends upon the materials selected, whereas σ_{max} depends upon materials as well as the structural geometry and the loading condition (tension, compression, shear).

In terms of major vehicle structural components which comprise the complete vehicle structure, we can write Eq. (25) in the general form

$$\frac{W_s}{V_g} = \sum_{i=1}^{n}\left(\frac{\bar{\rho}_s}{\sigma_{max}}\right)_i D_i \tag{26}$$

where

$$D_i = (N_{max})_i(k_s)_i(A/V)_i$$

It is valuable to have the weight fraction relationship in the form of Eq. (26) since for a complex vehicle such as an aircraft it is convenient to consider the major structural components consisting of wings, fuselage, and tail separately. For simpler vehicle forms such as missiles, launch vehicles, and ship hulls, it is possible to utilize Eq. (25) directly.

Structural Design Index

The results given by Eqs. (25) or (26) in terms of the structural design index are useful for two separate purposes, as demonstrated in Ref. 15. In one case, it provides a common basis for the evaluation of minimum weight materials and structural configurations. Secondly, it permits important generalizations concerning structural design trends among various vehicle types regardless of size.

As a specific example taken from Ref. 15, surface ship hulls and aircraft wings and tails can be characterized in an idealized form as stiffened box beams under bending. Minimum weight design results for various materials in optimized stiffened box beams are summarized in Fig. 6 in terms of the appropriate design index

$$D_i = M/h^2w = N/h \tag{27}$$

Also shown in Fig. 6 are maximum design index ranges representative of various types of vehicles. Such data have been gathered from a broad range of actual designs, and for box beam structures these data characterize the maximum values of the design index, at the midship section for surface ships and at the root section of aircraft wings and tails.

In a similar manner, aircraft fuselages, missile, and launch vehicles can be characterized as stiffened cylinders under bending or axial compression. Here, the design index is

$$D_i = 4N/d \tag{28}$$

Typical results in terms of this index are also shown in Fig. 6 for optimized longitudinal and frame-stiffened cylinders of various materials. Also shown is the maximum design index range corresponding to aircraft fuselages, missile, and launch vehicles.

As a final example, submarine pressure hulls can be treated as cylindrical pressure vessels under external pressure in terms of the design index

$$D_i = 2p \tag{29}$$

Figure 6 displays typical results for optimized stiffened cylinders of various materials in combination with the current design index range for deep-submergence pressure hulls.

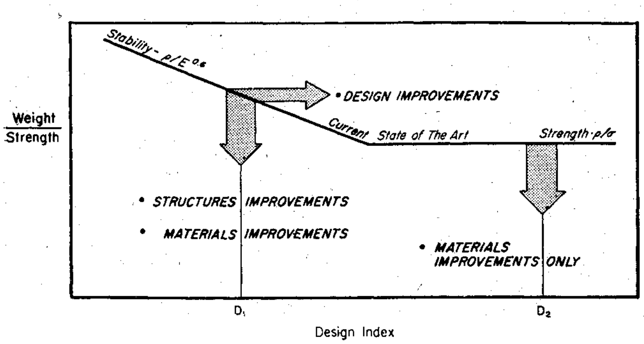

Fig. 7 Potential directions for improving weight/strength thereby reducing the structural weight fraction of vehicles.

The foregoing examples serve to indicate the comparative efficiencies of various materials in optimized structural components, and become particularly meaningful when related to the maximum design index range associated with various vehicle applications. From Fig. 6, it is quite apparent that the efficiencies of materials as used in current and projected fuselage, missile, and launch vehicle designs, and surface ship hulls are governed by stability limitations. Thus, improvements in materials are to be sought in terms of density and modulus. On the other hand, density and yield strength improvements are to be sought for supersonic aircraft wings and tails and deep-submergence pressure hulls as indicated in Fig. 6.

Directions for Materials Improvements

The rather surprising design generalization that emerges from Fig. 6 is that various structural applications are characterized by rather narrow maximum design index ranges. It is this fact which permits valid conclusions to be drawn regarding directions for material improvements in terms of stability or strength limitations for both current and projected designs.

The general structural design situation displayed in Fig. 6 can be summarized as shown in Fig. 7 in terms of possible directions for reduction of the structural weight fraction. If a given design application has a design index range corresponding to D_1, design, structures and materials (density, modulus) improvements can lead to greater weight/strength efficiency. On the other hand, for the design index range corresponding to D_2, only material improvements (density, yield or ultimate strength, ductility) can contribute to improved weight/strength efficiency.

In summary, then, starting with the generalization that the function of a vehicle is to efficiently transport a given payload a given distance, the structural weight fraction has been identified as the factor most sensitive to structures and materials improvement. Furthermore, the value of structural weight saving over the life of the vehicle can be large and thus relatively large costs can be expended in such endeavors. Analysis of the factors comprising the structural weight fraction has led to the important generalization that the structural design of the vehicle or its major components is characterized by rather narrow ranges of the maximum design index. It is this factor which dictates the specific improvements in materials (or structures) that can result in a meaningful reduction of the structural weight fraction.

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