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ROTORCRAFT WEIGHT TRENDS IN LIGHT OF STRUCTURAL MATERIAL CHARACTERISTICS

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ABBREVIATIONS AND SYMBOLS

cpr - Number of loading cycles per rotor revolution
E - Modulus of elasticity
F - Strength
G - Modulus of rigidity
N - Number of loading cycles
n_{cy} - Number of rotor loading cycles
rpm - Revolutions per minute rotor
s - Area
S - Stress
T - Time
V - Volume
VTO - Vertical takeoff
w - Weight per unit area
W - Weight
W*bl* - Relative weight, rotor blade group
Wcmp - Weight, major component
W*cmp* - Relative weight, major component
W*ds* - Relative weight, drive system group
We - Weight, aircraft empty
W*e* - Relative weight, aircraft empty
W*f* - Relative weight, fuselage group
W*fc* - Relative weight, flight controls group
W*fs* - Relative weight, fuel system group
W*h* - Relative weight, rotor hub and hinge group
W*lg* - Relative weight, alighting gear group
Wvmax - Weight, maximum vertical takeoff gross
δ - Specific gravity
γ - Specific weight
μ - Component weight fraction
η - Weight effectiveness index

SUBSCRIPTS

$_{b}$ - Bending
$_{c}$ - Compression
$_{e}$ - Endurance limit
$_{E}$ - Buckling and linear deflection
$_{fl}$ - Flight lifetime
$_{G}$ - Torsional deformation
$_{n}$ - Specific component or material, in general, or loading mode
$_{nlnm}$ - New material non-load carrying element
$_{nm}$ - New material
$_{nnm}$ - New material load carrying element
$_{nl0}$ - Baseline material non-load carrying element
$_{n0}$ - Baseline material load carrying element
$_{sh}$ - Shear
$_{t}$ - Tension
$_{tu}$ - Tensile ultimate
$_{wa}$ - Water
$_{0}$ - Baseline material

ABSTRACT

Variations in the weights of rotorcraft and their components due to advanced materials use are the topic of this study. The impact of new materials on component weights is illustrated by historical weight trends. The influence of structural material characteristics on the relative weight levels of rotorcraft components, the weight effectiveness, for both static and cyclical loadings is reviewed. Cursory expressions are developed to permit estimation of the affect of structural material strength effectiveness values on component relative weights. Special constraints which could limit possible weight reductions are considered briefly. Advanced structural materials that exhibit superior weight reduction potential are identified.

1. INTRODUCTION

Minimizing the empty to operational gross weight ratio (**We**) is critical to the success of any air transport design. This ratio is especially significant for aircraft operating in a vertical takeoff (VTO) mode, where **We** values dictate the level of useful load. The useful load, with fuel consumption per unit of gross weight and distance traveled, determines the payload that can be carried over a given range. **We** is equally important in payload versus endurance relationships.

The emphasis placed on achieving the lowest possible **We** during the design of any successful rotorcraft has always been significant. From the first production helicopter to the present, rotorcraft weight reduction has been strongly driven by a fundamental thought: the lowest rotorcraft relative empty weight can only be achieved by reducing all of the major rotorcraft components to their lowest possible relative weights. In turn, the relative weights of major components are strongly influenced by the characteristics of the structural materials used. The selection of structural materials results, ideally, from an optimum balance of strength, rigidity and weight characteristics.

This paper, based on a study performed for the U.S. Army Aviation Systems Command ([1]), presents efforts to reduce rotorcraft relative empty weight (**We**) historically It also shows how aircraft size, as expressed through the maximum vertical takeoff weight (**Wvmax**), can affect rotorcraft relative weights.

Temporal (time related) and size related trends for seven rotorcraft component groups are examined. Their influences on relative weights are presented in graphical form. Temporal influences are presented in graphs of relative weight versus year of entry into service. The influence of size is demonstrated in graphs of relative weight, both rotorcraft and component, versus **Wvmax**. Ideally, size influences should be presented for rotorcraft of similar vintage but, due to data limitations, relative weights are plotted against **Wvmax** without regard for the year of service entry. Both Western and Soviet designs are presented for comparison (including some conceptual designs).

Weight effectiveness criteria of materials are reviewed for a better understanding of the influence of their structural characteristics on component relative weights. This is done considering the repetitive loadings that most major rotorcraft components are subjected to. Consequently, weight effectiveness criteria are established at a specific number of cycles and computed with due consideration for both the life of the aircraft and its typical operational profile.

Cursory expressions are then developed using weight effectiveness concepts which permit rough estimates of component relative weights using different materials. In some cases special constraints limit weight reduction in actual designs. The need for a high moment of inertia on main rotor blades for autorotation is one example. Other operational and economic constraints may limit the practical use of some materials despite promising strength/weight characteristics. The influences of various loading modes on weight effectiveness indices are also developed and discussed.

Structural materials that exhibit superior potential for rotorcraft component weight reduction are briefly reviewed in the final section of this presentation. Some suggestions are offered to optimize the benefit of weight effectiveness indices to the rotorcraft community as a tool for comparison of materials and weight prediction.

2. TEMPORAL AND SIZE-RELATED RELATIVE WEIGHT TRENDS

2.1 General

Rotorcraft relative empty weight, and major component relative weights (as defined in [2]), are based on maximum vertical takeoff gross weight ($\mathbf{Wvmax}$). The relative empty weight ($\mathbf{W}\mathit{e}$) is defined as:

(1) $\mathbf{W}\mathit{e} = \mathbf{We} / \mathbf{Wvmax}$

where $\mathbf{We}$ is the rotorcraft empty weight. Any major component relative weight $\mathbf{W}\mathit{cmp}$ is defined as:

(2) $\mathbf{W}\mathit{cmp} = \mathbf{Wcmp} / \mathbf{Wvmax}$

where $\mathbf{Wcmp}$ is the component weight.

$\mathbf{Wvmax}$, rather than design gross weight, has been selected as the basis for the establishing comparative weight trends because it has readily apparent physical significance. In addition, $\mathbf{Wvmax}$ is usually more definitive in determining the actual rotorcraft operational load-carrying capability ([2]).

The components of (3) are some of the relative weight groups included in $\mathbf{W}\mathit{e}$. Their temporal and size-related relative weight trends were examined in [1] and are reported in this paper. The remaining relative weight groups that normally comprise $\mathbf{W}\mathit{e}$ will not be addressed here.

(3) main rotor blades ($\mathbf{W}\mathit{bl}$)
main rotor hub and hinge ($\mathbf{W}\mathit{h}$)
fuselage with cowlings ($\mathbf{W}\mathit{f}$)
landing gear ($\mathbf{W}\mathit{lg}$)
drive system ($\mathbf{W}\mathit{ds}$)
fuel system ($\mathbf{W}\mathit{fs}$)
flight controls ($\mathbf{W}\mathit{fc}$)

2.2 Temporal Variation Of $\mathbf{W}\mathit{e}$ - (Fig. 1)

The Sikorsky R-4, introduced into service in 1944, was the world's first production helicopter. The Mil Mi-1, which entered service in 1951, was the first Soviet production model. The $\mathbf{W}\mathit{e}$ for both was 0.79. Since then, $\mathbf{W}\mathit{e}$ values have descended as low as 0.41 in the West (MDHC 500E) and 0.50 in the USSR (Mi-26).

1950-1960 represented a period of rapid improvement in $\mathbf{W}\mathit{e}$ for Western and Soviet helicopters of all configurations. This can be attributed primarily to the replacement of reciprocating engines by much lighter gas turbines. From early 1960 to the present, gains in reducing $\mathbf{W}\mathit{e}$ have occurred at a slower rate. Progress can be judged by the optimal boundaries depicted for Soviet and Western rotorcraft.

The optimal boundaries indicate that Western technology is still capable of producing helicopters with the lowest **We**. From the actual points of helicopters in the 1980s, however, it appears that the average Western **We** is not as low as the optimal boundary indicates. It also appears from the Soviet hypothetical helicopter values, especially single rotor, that they intend to become more competitive.

Single and tandem rotor helicopters in the West appear to be progressing at the same rate in **We** reduction. In the USSR, the greatest progress in lowering **We** has been in single rotor helicopters. The values for Soviet hypothetical machines indicate that this improvement emphasis can also be expected in the future.

The **We** level for the current tilt rotor XV-15 (1983), is much higher than the average for contemporary helicopters. Current weight estimates for the V-22 tilt rotor (1990) show that its **We** should be much lower than XV-15. The Eurofar tilt rotor (1998) is expected to be even lower than the V-22 ([4]).

Moderate improvement in rotorcraft **We** from the 1960s to the present is partially due to increases in engine power/weight ratios. A substantial portion of the remaining improvement is likely to reflect the reduction in structural weights of the other major helicopter components.

2.3 Influence Of Rotorcraft Size (Wvmax) On *We* - (Fig. 2)

Since the optimal boundary may be interpreted as an indication of state of the art potential, it can be seen that for Western helicopters equally low **We** ratios can, in principle, be achieved for small, as well as large helicopters. However, looking at the overall distribution of points for the Western helicopters in Fig. 2 it appears that, on the average, there is some improvement in the **We** with size as far as pure helicopters are concerned. Data for Soviet helicopters, as expressed through optimal boundaries and the overall distribution of points, seems to support the trend of relative weight improvement with size.

2.4 Temporal Variation Of W*bl* - (Fig. 3)

The potential for achieving low Western helicopters **Wbl** values, as expressed by the optimal boundary, appeared in the early 1950s. The blades produced at the time reflected relative blade weights not much higher than those of contemporary helicopters. The overall distribution of **Wbl** points for Western designs, on the average, declines only slightly with time. This temporal trend exists in spite of the appearance of new structural materials with much improved strength/specific weight ratios. These new materials may be expected to contribute to a decrease in **Wbl**, but constraints such as rotor axial moment of inertia and blade coning angle requirements do not permit full advantage of the materials' potential to be realized in practice. This subject is more thoroughly investigated in [1]. It is also interesting to note that the relative scatter of Western points is not very large. The XV-15 in this case lies slightly above the optimal boundary.

From the limited Soviet statistical data available, it appears that from the early days of the Mi-1 and Mi-4, considerable progress in reducing relative blade weight has been made. In the case of the Mi-6 (1959) **Wbl** was reduced from 8.3%, for their original blades having steel tubular spars, to 6.4% in later designs (probably fiberglass). The same trend was observed for the Mi-8 (1965), where the relative blade weight was reduced from 5.6% for extruded Duralumin spars, to 4.8% for the glass fiber design. The **Wbl** for the Mi-2 (1965), 4.5%, is not much different than the optimal Western values. Points for the Soviet hypothetical helicopters seem to indicate that the objective is to attain the **Wbl** level of the optimal Western boundary.

2.5 **Influence Of Rotorcraft Size (Wvmax) On W*bl* - (Fig. 4)**

The shape of the optimal boundary for Western helicopters, as well as the distribution of points, seems to indicate that the W*bl*, as a function of **Wvmax**, attains its optimum value for medium size helicopters of the 10,000 to 20,000 lb. class. There seems to be a marked increasing trend in W*bl* values as the rotorcraft gross weight decreases from the 10,000 lb. level. In contrast, only a slight trend toward an increase in the relative blade weight level can be noted as the helicopter gross weight increases beyond the 25,000 lb. level. Within the 10,000 to 150,000 lb. maximum gross weight range, the average W*bl* level for Western helicopters does not seem to deviate much from 4%. It should also be noted that with few exceptions, the scatter of Western points about the 4% level is small.

It is difficult to establish the optimal boundary for Soviet helicopters at higher **Wvmax** values beyond that corresponding to the Mi-8 (approximately 26,000 lbs). Actual blade weights for such new designs as the Mi-26 and Mi-17 are not commonly available yet. It was shown ([2], [6]) that the Mi-26 is quite similar in many respects to the Tishchenko hypothetical helicopter. It may be assumed that its blade weights would also be not much different from those of the Tishchenko SR-52 helicopter. Based on this assumption the Soviet optimal boundary has been extended beyond the Mi-8 point. It appears from the so-established optimal boundary, as well as actual points, that the same conclusions as those derived for Western helicopters are feasible. W*bl* values tend to attain their optimal level for the 10,000 to 20,000 lb. **Wvmax** class. Beyond the boundary the values tend to sharply increase with a decrease in **Wvmax** below 10,000 lbs, and increases only moderately as **Wvmax** become higher than 20,000 lbs. It appears, in general that relative blade weights of Soviet helicopters tend to be slightly higher than those of their Western counterparts. The hypothetical helicopters ([5]), indicate that for single rotor helicopters in the upper medium **Wvmax** class (about 40,000 lbs.) they expect to achieve levels comparable to the optimal ones for Western machines. Large helicopters of the Mi-26 class, however, seem to be accepted by the Soviets with higher relative blade weights than those of the West for both single and tandem rotor helicopters.

2.6 **Temporal Variation Of W*h* - (Fig. 5)**

The Western helicopter optimal boundary sustains an almost constant level of slightly below a 4% value from the 1950s to the early 1970s. Then, in the 1980s, it descends to a level slightly below 3%. The decreasing trend in W*h* values, similar to that of the optimal boundary, can also be noted by examining the overall distribution of Western helicopter points in Fig. 5. It is interesting to note that for the tilt rotor represented by the XV-15, W*h* is quite close to the optimal boundary for Western helicopters. It should also be noted that a considerable drop in the W*h* level occurred in those cases where steel hubs were replaced by those made of titanium. In turn, replacing titanium hubs with hubs made of composite fiber materials led to a further reduction in W*h*. This clearly illustrates the influence of materials having better strength/specific weight ratios.

In spite of the limited amount of data available on Soviet helicopters, the following tentative observations can be made. Although, through the years, the W*h* levels of Soviet helicopters generally were above those for Western machines, there is an exception in the Mi-2 case, where its W*h* level is on the optimal boundary for Western helicopters. As far as future trends and efforts are concerned, there appears no projection (and probably, little effort) to attain the optimal Western W*h* level for all configurations and sizes of helicopters. This latter aspect will be more clearly visible in Fig. 6.

2.7 Influence Of Rotorcraft Size (Wvmax) On W*h* - (Fig. 6)

On the optimal boundary for Western helicopters, it appears that the lowest **W*h*** level of about 2.7% is achieved for the 20,000 lb. **Wvmax** class machines. For both lighter and heavier helicopters, the optimal **W*h*** values tend to increase, reaching approximately 3.9% for the 5,000 lb. , and 5% for the 140,000 lb. **Wvmax** machines. However, the overall distribution of the **W*h*** points seem to suggest that, on the average, the relative weights of the hubs and hinges stay at about the 4% level, although the scatter of **W*h*** values is considerable. It is also clear that a transition to structural materials with better strength/specific weight ratios (e.g., from steel to titanium, or from titanium to composites) results in considerable weight savings. It is also interesting to note that the tilt rotor (XV-15) **W*h*** is on the helicopter optimal boundary.

There are not enough points for Soviet helicopters in Fig. 6 to positively define an optimal boundary for **W*h*** values. However, it appears that, in general, the relative hub and hinge weights of Soviet production helicopters are higher than those of their Western counterparts. The Mi-2 represents an exception, as its **W*h*** point is right on the optimal boundary for Western helicopters. In contrast, points for the Mi-6 and Mi-10 are well above the Western trend with **W*h*** approximately 7.8% for the Mi-6 and about 8.8% for the Mi-10 helicopter. As to indications of future trends, it should be noted that for the single rotor of about 38,000 lbs., low **W*h*** values of about 4% are visualized (right on the optimal boundary of Western helicopters). For the large single rotor machines of the Mi-26 **Wvmax** class (130,000 lbs.), Soviet goals are mor conservative (**W*h*** approximately 6%). Projections for side-by-side helicopters of the Mi-26 gross weight class appear quite optimistic with **W*h*** approximately 3.7%, below the Western optimal boundary.

2.8 Temporal Variation Of W*f* - (Fig. 7)

In spite of a considerable scatter of points for Western rotorcraft a general trend emerges which indicates a decrease in **W*f*** with time. This trend becomes even more noticeable on the optimal boundary. Also, looking at this boundary, it should be noted that relative fuselage weights for cranes (CH-54 and YCH-62A) are below the line representing optimal **W*f*** values of other Western configuration. The point corresponding to the tilt rotor (XV-15) shows that its **W*f*** value is higher than points representing other contemporary rotorcraft.

It is more difficult to establish temporal trends in **W*f*** values for Soviet helicopters, since these investigators have no reliable data regarding fuselage weights for Soviet rotorcraft of the 1970s and 1980s. However, as in the preceding cases, assuming that the hypothetical single rotor helicopters closely resemble achievable weight levels, a tentative optimal boundary has been extended in Fig. 7 between the years 1968 and 1983. Looking at this line and the general distribution of Soviet **W*f*** points, it may be concluded that, as in the West, there should be a trend in the USSR toward a decrease in **W*f*** levels with time. Nevertheless, it appears that, as in the past, Soviet relative fuselage group weights would remain somewhat above that of their Western counterparts.

2.9 Influence Of Rotorcraft Size (Wvmax) On W*f* - (Fig. 8)

There is considerable scatter in the **W*f*** values for each **Wvmax** class of Western helicopters. Within this scatter it appears that the relative fuselage weights of tandems tend to be noticeably higher than those for single rotor helicopters. The Western optimal boundary indicates that potential for the lowest **W*f*** values is with single rotor helicopters of 20,000 to 25,000 lbs. The cranes exhibit **W*f*** levels considerably below those of their non-crane counterparts. Tilt rotor **W*f*** deviations seem more favorable when compared with helicopters than would appear from Fig. 7.

In attempting to establish the **Wvmax** related trend in **W*f*** values for Soviet helicopters, it can be noted that once the point on the extreme left (Mi-1) is excluded, the relative fuselage weights of the Mi-2 through Mi-12 are consistently close to 12%. The Mi-6 and Mi-10 are exceptions, having **W*f*** values of 14.3% and 13.4%, respectively. From points for Soviet helicopters for which data is available, it appears that their **W*f*** values seem to be higher than for single rotor Western designs. With little substantial data available for relative fuselage weights of Soviet helicopters from the 1970s to the 1980s, it is assumed that the values derived from the hypothetical single rotor helicopters ([5]) give an indication regarding the trend. Following this reasoning, it appears that Soviet designers are reducing **W*f*** to levels comparable of those in the West, and may have already done so.

2.10 General Remarks Regarding Trends In Landing Gear Relative Weight

There are three basic types of landing gear being used in rotary wing aircraft: (1) skids, (2) fixed, and (3) retractable. The fixed and retractable types are normally wheeled. Within the most numerous group, fixed, a special sub-group of tall landing gear may be identified for cranes and heavy lift helicopters. The relative weight trends are different for each of the above-mentioned types of landing gear. Some investigators of the weight aspects of landing gear ([5]) tend to establish trends separately for single and tandem rotor helicopters. In the present study, the potential differences are not considered large enough to warrant establishment of separate subdivisions.

2.10.1 Temporal Variation Of W*lg* - (Fig. 9)

It can be noted that Western skid landing gear reflects little change in relative weight over the years, with the **W*lg*** value being slightly above 1% of **Wvmax**. An exception is the BO-105 helicopter with **W*lg*** approximately 2%. The relative weights of fixed landing gear, when judged in the light of the optimal boundary and actual point distribution, seems to indicate a decline in **W*lg*** values with time. **W*lg*** approaches 2.2% in the 1980s. The relative landing gear weight of the heavy lift helicopter is considerably higher than the optimal boundary. Retractable landing gear **W*lg*** values can be expected to be higher than for fixed. The CH-53E, with **W*lg*** of 1.7%, represents an interesting exception. The tilt rotor (XV-15) has considerably higher **W*lg*** than conventional helicopters.

The **W*lg*** optimal boundary for contemporary Soviet helicopters was established using hypothetical helicopters ([5]), due to a lack of actual data. Except for the Mi-12, **W*lg*** points for all other actual helicopters appear quite close to the optimal boundary. The trend suggested by this boundary, similar to the Western case, is a slight decline with time in the **W*lg*** of Soviet designs. The tall landing gear of crane helicopters result in a much higher **W*lg*** than normal undercarriages. It should also be noted that the relative weights of Soviet fixed landing gear are generally quite close to those of their Western counterparts. Soviet retractable landing gear is represented by a point for a hypothetical helicopter ([5]). The anticipated **W*lg*** level appears similar to those of some Western rotorcraft.

2.10.2 Influence Of Rotorcraft Size (Wvmax) On W*lg* - (Fig. 10)

The relative weights of Western skid landing gear do not seem to be strongly influenced by changes in **Wvmax**. Similarly, **W*lg*** levels for fixed landing gear appear to be only slightly affected. The above average **W*lg*** for the heavy lift helicopter can be attributed to the specific configuration of its landing gear rather than **Wvmax**. There are currently not enough points for Western rotorcraft with retractable landing gear to establish a meaningful trend.

The **W*lg*** trend of Soviet helicopters is almost constant with **Wvmax** for fixed landing gear. The optimal boundary appears to represent the average **W*lg*** line. Extending the optimal boundary using data for hypothetical helicopters ([5]) supports the trend of constant **W*lg*** versus **Wvmax**. Similar to the case of Western heavy lift helicopters, the high values of **W*lg*** representing the crane and side-by-side helicopters are exceptions resulting from specific landing gear configurations. There is insufficient data available regarding Soviet retractable landing gear to establish a trend of **W*lg*** versus **Wvmax**.

2.11 General Remarks Regarding Trends In Drive System Relative Weight

Weight predictions of drive systems usually include separate estimates for gearboxes and shafts. It may also be anticipated that the magnitude of torque transmitted through various parts of the system will be a main factor in determining the system weight. Consequently, characteristics such as installed power and overall transmission ratio would be a stronger influence on drive system weight than **Wvmax**. The influence of power and transmission ratio on transmission weight is discussed in [1]. However, since this paper is aimed at presenting the influence of major component relative weights on **W*e***, the philosophy of relating component weights to **Wvmax** will be maintained.

2.11.1 Temporal Variation Of W*ds* - (Fig. 11)

The scatter in **W*ds*** values is not as high as anticipated for Western helicopters. The optimal boundary indicates that there exists a potential trend toward reduction of **W*ds*** with time, in spite of a tendency to install and use more power per pound of **Wvmax** in newer aircraft. It should be emphasized, however, that the trend toward decreasing **W*ds*** values with time is slight, and the average trend appears almost constant at about 8%. The tilt rotor (XV-15) has a higher **W*ds*** than corresponding helicopters.

Soviet helicopters exhibit trends similar to those of their Western counterparts. Their optimal boundary for existing machines also runs very close to that of the West. A tentative extension of that boundary based on Soviet hypothetical helicopters also remains close to Western projections. In addition, there is a similarity in the scatter of points for the two design schools.

2.11.2 Influence Of Rotorcraft Size (Wvmax) On W*ds* - (Fig. 12)

No definite trend appears from the optimal boundary for Western rotorcraft **W*ds*** versus **Wvmax**. The distribution of the average values also gives the impression that, similar to the temporal trend, the **W*ds*** level remains almost constant with respect to **Wvmax** (about 8%). The trend indicated in the previous figure is confirmed here with respect to the tilt rotor (XV-15): **W*ds*** is higher than for helicopters of the same weight class.

It is not possible to establish a clearly defined optimal boundary for Soviet helicopters. It is interesting to note that the authors of [5] do not visualize any reductions in **W*ds*** values below traditional levels for the hypothetical helicopters except the 33,000 lb. class single rotor. Furthermore, for the 114,000 lb. tandem, they visualize relative drive system weights higher than those for the single or side-by-side rotor helicopters of the same weight class, and considerably higher than for the Western tandem heavy lift helicopter (YCH-62A).

2.12 General Remarks Regarding Trends In Fuel System Relative Weight

In weight prediction methods, the weight of the fuel system is usually directly related to the fuel capacity of the aircraft. Furthermore, it may be expected that the weight of this system will be strongly affected by factors such as survivability and crash-resistant requirements. For this reason, it may be anticipated that a large scatter will be encountered if fuel system weight is related to **Wvmax**. To maintain consistency, despite the adverse effects, **Wvmax** will be used as basis for comparison.

It should also be noted that the average Wfs is 1.6% and changes in Wfs values woul have only a secondary effect on We when compared with the influence of other major c ponent relative weights. For these reasons, only a brief examination of **Wvmax** related trends is performed here.

2.12.1 Temporal Variation Of Wfs - (Fig. 13)

Though the data shown is limited, Wfs values for Western rotorcraft are scattered, as predicted. Further insight indicates that the higher Wfs values (up to 2.1%) represent military helicopters, with crash-resistant and survivable fuel systems. The optimal boundary remains practically constant versus time near the 1.1% level.

The optimal Wfs boundary for Soviet rotorcraft stays very close to its Western counterpart until the mid-1960s. It then descends with a future projected level of only 0.8%. The Wfs scatter of actual and hypothetical rotorcraft is comparatively low. It would be interesting to obtain data for Soviet combat helicopters incorporating survivable and crash-resistant features, to see how their Wfs values fit into the general trend.

2.12.2 Influence Of Rotorcraft Size (Wvmax) On Wfs - (Fig. 14)

No visible trend is apparent in the variations of Wfs as a function of **Wvmax** for Western helicopters. Closer examination will show, as indicated in the preceding subsection, that the Wfs value is primarily influenced by crash-resistant and survivable fuel system features, and not by rotorcraft size.

The Soviet helicopters presented, which apparently have no crash-resistant or survivable fuel system features, have optimal boundary ordinates which remain practically constant throughout the weight range. Wfs values for other points do not excessively deviate from the optimum.

2.13 General Remarks Regarding Trends In Flight Control Relative Weight

As in the case of the drive system, weight prediction procedures for flight controls usually include separate estimates for subsystems. The cockpit and remaining control weights, including the boosting systems are typically separate items. Again, as with the drive system, only the overall system relative weight will be considered.

2.13.1 Temporal Variation Of Wfc - (Fig. 15)

The optimal boundary for Western helicopters suggests a potential for reduction of Wfc values with the progress of time. However, when the overall distribution of the relative weight points indicates that the temporal decrease in the Wfc level is, on the average, much smaller than could be anticipated from the optimal trend. The tilt rotor (XV-15) can be expected to have a much higher Wfc than conventional helicopters due to the presence of nacelle-attitude controls.

The temporal trend for Soviet helicopters can be noted to be similar to that of the West. The Soviet optimal boundary, for instance, extended toward **W*fc*** for hypothetical helicopters, seems to indicate both an actual trend and a conscious effort toward reduction of the relative weight of flight controls. It also appears that despite high **W*fc*** for the existing side-by-side helicopter (Mi-12), they hope that in the future, the relative weight of flight controls for the side-by-side helicopter can be kept on the same level as for single rotors.

2.13.2 Influence Of Rotorcraft Size (Wvmax) On W*fc* - (Fig. 16)

With respect to Western helicopters, once the points representing helicopters with little boosting are excluded, there appears to be little change in the optimal boundary as a function of the **Wvmax** values, staying close to the 4% **W*fc*** level. The overall distribution of the **W*fc*** points as well does not lead to the detection of any clear pattern of the variation in the relative weight of the flight controls with respect to **Wvmax.** The tilt rotor point (XV-15) indicates that, as previously state that the **W*fc*** value for this configuration is more than two times higher than for helicopters of the same weight class.

For Soviet helicopters the optimal boundary (extended toward hypothetical machines) also appears, as in the case of Western helicopters, close to 4%. As for future trends, only moderate reductions in relative weights of flight controls are expected. It is interesting to note that similar levels of **W*fc*** values are projected for all configurations (single, side-by-side, and tandem rotor), in spite of the fact that the actual relative weight of the flight controls of the Mi-12 side-by-side helicopter is well above those for single rotor types.

2.14 Discussion - (Fig. 17)

In Fig. 17 relative weights representing the contemporary state of the art for the seven major helicopter components discussed in this paper are shown in the order of their decreasing values. The relative major component weights were determined by computing their average values for the Western helicopters appearing within the 1975 to 1985 year limits in figures showing temporal trends in relative component weights. The component relative weight values corresponding to the optimal boundary in the 1980s are also marked in this figure. This should give the reader an idea of the major component contributions to **W*e***, and the possibilities that exist for reducing their relative weights.

Possibilities for further reduction of the component relative weights can be examined once some quantitative relationships describing the influence of strength (or rigidity) and specific weight characteristics on the weight levels of rotorcraft components are established. This will be done in the following chapter.

3. INFLUENCE OF MATERIAL CHARACTERISTICS ON STRUCTURAL ELEMENT WEIGHTS

3.1 General

Once the relationships between the weight of simple structural elements, various loading modes, and principal characteristics of various materials have been reviewed variations in the relative weights of the major rotorcraft components can be accomplished by singling out the type of loading (tension, compression, torsion, elastic deformation, etc.), acting on the most important structural elements of the considered component. In this analysis, it should be remembered that structural elements of all rotorcraft are usually subjected to repeated loads of various frequencies. Thus, the allowable stress level would be dictated by the number and type of cycles accumulated throughout the operational life of the aircraft. The magnitude of the total number of cycles will be influenced by the following three major parameters: (1) intended operational life, (2) type and size of aircraft, and (3) mode (also known as profile) of typical operations. Consequently, all three aspects must be somehow reflected in establishing the relationship between principal material characteristics and the weight of the components.

With respect to the presentation of the influence of new materials on the component weight, it appears that one of the most suitable methods would be to establish the ratio of the relative weight of a major component fabricated from advanced materials to that of the corresponding component fabricated from traditional materials. In other words, the "traditional" component would serve as a baseline for measuring the actual or potential progress in structural weight reduction through the application of advanced materials.

3.2 Weight Effectiveness Indices

Out of many possible ways of determining the weight effectiveness indices of structural materials, those based on the ratio of the allowable stress, or moduli levels to the specific gravity of material appear well suited for examining the influence of new materials on relative weights of rotorcraft components ([1]). The so-defined weight effectiveness index (η_n) for elements and components whose dimensions are dictated by the allowable stress S_n becomes:

(4) $\eta_n = S_n / \delta$

where subscript n stands for the type of loading (torsion, compression, bending, and shear) and δ is the specific gravity of the structural material.

(5) $\eta_n = E / \delta$ for linear type elastic deformation

(6) $\eta_n = G / \delta$ for torsion

where E is the modulus of elasticity and G is the modulus of rigidity.

3.3 Fatigue Effects On Weight Effectiveness Indices

In estimating the weight effectiveness index values it should be remembered that the moduli of elasticity and rigidity of metals would remain the same within the whole possible operational envelope and time of rotorcraft operation. However, composite structures, especially those consisting of laminates with various orientations of fibers, when subjected to repetitive loadings, may undergo progressively increasing delamination which, in turn, would slightly lower the E level of the structure [7].

In contrast to the above-indicated "no", or "very small" effects of repeated loading on the E and G levels, the breaking and hence, allowable stress on metals as well as composites (be it tension, compression, bending, or shear), would vary considerably with the total number of loading cycles (N), and other factors such as loading configuration, stress concentrations, surface condition, environmental conditions, and material processing parameters.

Partially because of the above reasons and partially because of the additional uncertainty regarding the number of cycles that may be encountered at a particular stress level during the operational life of a component, rotorcraft designers tend to accept much lower allowable stress level values (S_{al}) than those actually given by the S-N curve.

Furthermore, experimental data on the effects of repeated loading on the breaking stress are seldom available for the total number of loading cycles, especially at $N<10{,}000$. However, there are some components (e.g., landing gear and transmissions), where maximum loadings occur only infrequently, for instance during takeoffs and landings. Consequently, the total number of critical loading cycles acquired during the operational life of the rotorcraft may be below the N level for which experimental data is available. In view of this, methods were developed for establishing the shapes of the **S-N** curves for the total range of loading cycles ($1<=N<=N_e$), where N_e is the number of cycles corresponding to the endurance limit (S_e), i.e., a point where further increase in the number of loading cycles does not produce any decrease in the breaking stress.

In this respect, a method originally proposed in the 1960s by Albrecht [8] and recently refined may be used for determinations of the **S-N** curve for the allowable stresses throughout the whole range of repeating cycles [9]. One approach presented in [9] permits the generation of nondimensional **S-N** curve shapes for steel and aluminum alloys using only available high-cycle fatigue data. These generalized curves, expressing the ratio of alternating breaking, or lower allowable stresses, to ultimate tensile allowable (F_{tu}) are plotted as a function of the number of cycles (Fig. 18). When representative loading cycles occur in the presence of a steady load, the shape of the **S-N** curve would change, depending on the magnitude of the steady stress to the ultimate [9].

Once S_{al} as a function of N is known, the weight effectiveness indices for various materials and/or loading modes, etc., can be computed by using the relationships given in section 3.2. As an example, the S_{al}/δ versus N curves are shown in Fig. 19 for 4130 steel and 24S-T aluminum alloy.

The above-outlined approach for predicting the total **S-N** curves, based on [9] can be extended to nonmetallic materials such as composites. Basic information regarding the fatigue properties of metallic structural materials can be found in such publications as Military Handbook-5D [10]. However, there is no similar single source of information regarding fatigue properties for composites. Consequently, the necessary data must be assembled from such publications as company brochures and professional journals.

3.4 Influence Of Life Span On Component Weight

The rotorcraft manufacturer usually specifies two types of life for major components. One is chronological (calendar years of service) and another is the operational life (total flying time). However, it appears that only operational life (T_{fl}, hr) will affect the component weight.

During the operational life of a rotorcraft, its components experience two types of repeating loadings. One, depending on the anticipated number of operational events (e.g., takeoffs and landings and high-load flight maneuvers) expected to occur during the operational life of a rotorcraft, and the other, having its source chiefly in the rotation of the lifting rotors. The first type is considered to be infrequent in comparison with the second. However, absolute numbers of such events encountered during the life of the rotorcraft may be quite high. For instance, during one logging operation, some helicopters encountered as many as 720,000 trip cycles. Although in each of these events, there were no takeoffs and landings, the power excursions frequently varied from zero to rated power [9]. The whole area of estimating the total number of the critical loading cycles acquired during the operational life of a rotorcraft by its various components in conjunction with the operational profile, is becoming increasingly important, as witnessed by the increasing number of studies and publications (e.g., [9], [11], and [12]) dealing with the subject.

With respect to loadings whose origin may be traced to the rotational motion of the lifting rotors, the total number of loading cycles acquired through "normal" operation during the flight life of a helicopter can be expressed as follows:

(7) $(n_{cy})_{fl} = 60(rpm) * T_{fl}(cpr)$

where rpm is the rotor revolutions per minute, T_{fl} is the total projected component life span expressed in flight hours, and cpr is the number of loading cycles per revolution. For contemporary helicopters whose major components usually have a specified life span of at least 5,000 hours, the numbers of 1/rev cycles will be very large, even for the **Wvmax** class over 100,000 lbs. (Fig. 20). It may be anticipated that the endurance limits of structural materials for rotorcraft components whose dimensions are dictated by repeated loads appearing at the 1/rev and higher cpr values represent a decisive factor for component weight.

3.5 Cursory Estimates Of The Influence Of Weight Effectiveness Indices On Component Weights

3.5.1 General

One of the simplest ways to make a preliminary estimate of the influence of advanced structural materials on the weight of a component would be to establish a ratio between the weight of a component structured of new materials to the baseline weight of an existing component. Once the absolute, or relative weight of the baseline component is known, either by actual weight or through reliable calculations, the procedure for evaluating the impact of new materials on that weight will be the same. In the most general case, baseline and new components may be considered as being composed of non-load and load carrying elements.

3.5.2 Non-Load Carrying Elements

Assuming that the baseline component weight is W_{ne}, the weight of the non-load carrying elements (W_{nle}) can be expressed as:

(8) $W_{nle} = \mu_{nle} W_{ne}$

where μ_{nle} is a weight fraction depicting the part of the total baseline component weight consisting of non-load carrying elements. Depending on whether W_{nle} represents the weight of a volume of material (e.g., fillers), or a surface (e.g., various non-load carrying panels and surfaces), the weight of the non-load carrying elements can be expressed as:

(9) $W_{nle} = V_{nle} \gamma_{ne} = V_{nle} \gamma_{wa} \delta_{ne}$

where V_{nle} is the volume of non-load carrying elements, γ_{wa} is the standard specific weight of water, and δ_{ne} is the material specific gravity. Or, alternately:

(10) $W_{nle} = s_{nle} w_{ne}$

where s_{nle} is the non-load carrying surface area of the considered component, and w_{ne} is the weight per unit of surface. Assuming that either volume (V) or surface area (s) of the component made of new material is the same as that of the baseline component, the weights of non-load carrying components (W_{nlnm}) become:

(11) $W_{nlnm} = V_{nle} \gamma_{wa} \delta_{nnm}$ for volume

(12) $W_{nlnm} = S_{nle} w_{nnm}$ for surface

Multiplying the right sides of Eqns. (9) and (10) by $(\delta_{ne}/\delta_{ne})$ and $(\mathbf{w}_{ne}/\mathbf{w}_{ne})$ respectively, and noting that $v_{nle}\gamma_{wo}\delta_{ne} = \mathbf{W}_{nle} = \mu_{nle}\mathbf{W}_{ne}$ and $s_{nle}\mathbf{w}_{nle} = \mathbf{W}_{nle} = \mu_{nle}\mathbf{W}_{ne}$, these equations can be rewritten as:

(13) $W_{nlnm} = \mu_{nle}\mathbf{W}_{ne}\ (\delta_{nnm}/\delta_{ne})$ and

(14) $W_{nlnm} = \mu_{nle}\mathbf{W}_{ne}\ (\mathbf{w}_{nnm}/\mathbf{w}_{ne})$

3.5.3 Load Carrying Elements

In the most general case, a major rotorcraft component may contain various elements whose dimensions and hence, their weight, are related to the loading mode in which they are working; namely, tension, compression, bending, shear, elastic buckling, or linear deflection and torsional deflection. The fraction of the total component weight, which is taken by all of the above-listed loading modes will be expressed through the following symbols: tension μ_t, compression μ_c, bending μ_b, shear μ_{sh}, buckling and linear deflection μ_E, and torsional deformation μ_G. Consequently, the absolute weight of all the baseline components elements working under a particular loading mode. Tension, for example, would be:

(15) $\mathbf{W}_{te} = \mu_{te}\mathbf{W}_{ne}$

Similar equations can be written for other groups of elements.

When new structural materials are substituted for those used in the baseline component, the influence of this substitution on the weight can easily be determined, using an approach similar to that outlined in the case of non-load elements. However, this time, ratios of weight effectiveness indices for the baseline and new materials would replace those of specific gravity (Eqn. (13)), or weights per unit of area (Eqn. (14)). Thus, when made of new materials, the total weight of all the components working in tension will be:

(16) $\mathbf{W}_{tnm} = \mu_{te}\mathbf{W}_{ne}\ (\eta_{te}/\eta_{tnm})$

3.6 Weight Of A Component With New Materials In Relation To That Of The Baseline

Taking into account both non-load carrying and load carrying elements, the weight of a major rotorcraft component built from new materials ($\mathbf{W}_{nnm}$) can be expressed through the baseline component weight ($\mathbf{W}_{ne}$) as follows:

(17) $$\mathbf{W}_{nnm} = \mathbf{W}_{ne}[\mu_{nle}(\delta_{nnm}/\delta_{ne}) + \mu_{nle}(\mathbf{w}_{nnm}/\mathbf{w}_{ne}) + \mu_{te}(\eta_{te}/\eta_{tnm}) + \mu_{ce}(\eta_{ce}/\eta_{cnm}) + \mu_{be}(\eta_{be}/\eta_{bnm})$$
$$+ \mu_{she}(\eta_{she}/\eta_{shnm}) + \mu_{Ee}(\eta_{Ee}/\eta_{Enm}) + \mu_{Ge}(\eta_{Ge}/\eta_{Gnm})]$$

The ratio $(\mathbf{W}_{nnm}/\mathbf{W}_{ne})$ of the new component weight to that of the baseline will be give by the expression contained in the brackets of Eqn. (17).

3.7 Discussion

It should be noted at this point that the cursory expression given by Eqn. (17) can be refined. This can be done by taking into account that the weight fractions (μ's) of elements working in a given loading mode in the new component may be different from those in the baseline. A study of the possible gains in accuracy resulting from this approach would be beneficial.

In order to facilitate the whole process of investigating the influence of new structural materials on the weight of major rotorcraft components, it would be desirable to develop a library consisting of weight effectiveness indices for rotorcraft structural materials (similar to those shown in Fig. 19), where values of the indices would be shown for the whole range of loading cycles from $N = 1$ to that corresponding to the endurance limit. Furthermore, this should be done for various stress ratio (R) values, surface conditions, and several steady load values (for example, 12.5%, 25%, and 50% of ultimate).

It should also be noted that in some cases, not all weight gains due to advanced materials as indicated by the procedures described in this chapter can be realized in practice. The case of rotor blades is discussed in [1].

4. ADVANCED STRUCTURAL MATERIALS AND THEIR APPLICATION TO ROTORCRAFT

4.1 General

In recent years, considerable progress has been made in the development of new structural materials, both metallic and nonmetallic, representing a great potential for reducing the relative weights of major rotorcraft components. These materials can be divided into three categories: (1) pure homogeneous metallic (steels and light alloys), (2) nonmetallic composites (usually based on high strength fibers embedded in resins), and (3) metallic-nonmetallic composites (for example, combining metallic elements with high strength fibers through a resin-type connecting medium).

Although many of the new advanced structural materials represent a clear-cut advantage from the point of view of the weight of the rotorcraft component, the application of these materials to practical designs encounters various constraints which can be grouped into economic and operational categories. With respect to the first class, the costs of materials and manufacturing often represent a strong constraint. These aspects were considered in detail in [13], [14], and [15]. Some hesitation in applying composites more widely can be attributed to operational concerns. The lack of long-term experience with their behavior, especially crack propagation and delamination when exposed to various environmental conditions, creates concerns for reliability and maintainability, and ultimately safety. The effects of other aspects of the operational environment are also currently unknown.

Nevertheless, in spite of all the above-mentioned constraints, there seems to be a growing trend toward an ever-increasing use of nonmetallic materials, especially composite materials, in the manufacture of major rotorcraft components. This trend is clearly visible in Europe (Fig. 21) and the U.S., where there is also a strong increase in the use of composite structural materials in rotorcraft. In new concepts such as the V-22 tilt rotor (Fig. 22) the structural composites may constitute as much as 30% of W_e ([16] and [17]). The trend toward a broader use of composites in helicopter structures can be seen in Soviet schools of design, and also in other countries ([18]).

4.2 Remarks Regarding Structural Materials

Although the term "advanced structural materials" is usually associated with composites either based on, or incorporating, high strength fibers, it should not be overlooked that considerable progress has been, and is being, made in the improvement of homogeneous metals, especially light alloys. In this respect aluminum-lithium alloys appear quite promising. The fixed wing industry in particular, both in the U.S. and Europe, seems to favor their application on a large scale. This position is motivated by the fact that replacing current aluminum alloys with new aluminum-lithium alloys can cut weight by 8% at a very small change in the overall cost ([14], and see also [20]). Composites are even more promising, offering the possibility of a 25% weight saving over metal construction for primary structures. But cost constraints and uncertainties regarding operational aspects dictate a rather cautious approach regarding the use of composites by fixed wing designers. Commercial transport designers hesitate to use composites in spite of the fact that the structural weight reducing potential in fixed wing aircraft has been demonstrated in many experimental aircraft (e.g., Rutan's Voyager **We** was approximately 16%).

In contrast to the fixed wing industry's hesitation (especially in the segments related to transport aircraft), rotary wing designers appear willing to bypass the modest structural weight savings offered by advanced aluminum alloys and go directly to a broad application of advanced composite materials.

An additional incentive for taking this approach is the possibility of creating components with optimal dynamic and aerodynamic characteristics. An all-composite main rotor blade is a leading candidate for possible aerodynamic/dynamic optimization. It should be pointed out that experimental composite blades were developed as early as 1948 (Cornell Aero Lab), and improved versions have been in U.S. production helicopters since the late 1970s.

Weight saving potential of composites become apparent when graphs or tables showing their weight effectiveness indices in comparison with those of metals are observed ([1]). One such comparison in bar chart form is shown in Fig. 23, while fatigue aspects are illustrated in Fig. 24.

5. CONCLUDING REMARKS

5.1 General Conclusions

Investigation of the historic trends in relative empty weight (**We**) of helicopters coupled with studies of the effect of aircraft size (expressed through **Wvmax**) indicated a rapid decline in **We** values through the 1950s for all gross weight classes of Western and Soviet designs. This was followed by a much slower decrease in **We** levels from the 1960s to the present. **We** of the existing tilt rotor (XV-15) is well above the corresponding helicopter levels. The **We** values projected for future tilt rotor designs (the U.S. V-22 and European EUROFAR) are still above those of their helicopter counterparts.

The rapid decline in helicopter **We** values during the 1950s and early 1960s was, to a large extent, due to the transition from reciprocating to gas turbine powerplants. This change reduced the relative engine weight levels from about 9.5% for helicopters of the early 1950s to about 3.5% for contemporary models. Further improvements in the specific weights of powerplants would exert little influence on **We** values for pure helicopters. **We** for new rotorcraft concepts with power loadings lower than helicopters could be significantly influenced by relative powerplant weights.

Graphs showing relative weights of components and their optimal boundaries should provide a clear and comprehensive insight into the process of achieving certain **We** levels. Such graphs would prove especially useful for concept formulators and designers of helicopters and new rotorcraft concepts. They would provide a basis for making realistic weight assumptions for new designs and provide standards for assessing the weight effectiveness of the design, as well as individual components. However, in order to retain their usefulness, such trend graphs must be continuously updated to reflect the most current information available.

Although somewhat slower than before the early 1960s, the steady decline in **We** helicopter values must be attributed to a general lowering of the relative weight values of components (excluding those of engines). The rate of decline, however may not be expected to be the same for all components. For example, temporal relative weight trends of lifting rotor blades for Western helicopters show only a gradual decline in W_{bl}. Soviet values initially decline rapidly, but gradually level off. This results from strong constraints regarding certain values for the blade moment of inertia. However, some reductions in W_{bl} through application of highly weight effective structural materials appear theoretically possible ([1]).

The decline in relative weights of major helicopter components is chiefly due to the application of new structural materials, exhibiting increased strength as well as elongation and rigidity moduli to specific weight ratios (weight effectiveness indices). Knowledge of the weight effectiveness indices for materials used in the baseline component and those in a new design should enable at least a rough estimate of the relative weight ratios of the new to the original components to be generated. However, in this process, weight effectiveness indices should be determined with due consideration of the loading conditions of various elements, taking into account such factors as number of loading cycles during the anticipated operational life of the component, loading modes (R values), and state of the surface.

Weight effectiveness indices point toward an increasing use of composites as structural materials in rotorcraft in spite of some initial reluctance caused by high cost and operational unknowns. Thus, a definite trend toward wider acceptance of nonmetallic materials in helicopter structures may be observed. In new rotorcraft concepts, such as tilt rotors or x-wings, the use of composites has become a 'must' in order to achieve the W_e levels necessary to compare favorably with conventional helicopters in VTO operations.

5.2 Recommendations

Data on materials currently available, and available in the near future, should be assembled. The most suitable and comprehensive ways of presenting the weight effectiveness indices of materials should be established.

The mathematical expressions and computational procedures for predicting the influence of new structural materials on the weight of major rotorcraft components should be expanded and refined. New materials should be compared with baseline materials to evaluate the the actual benefits of substitution, and the results archived for reference. The prediction methods should be validated against experimental data and modified to ensure fidelity.

Data on the materials and prediction methods available should be continuously reviewed, and revised as necessary to maintain currency and accuracy. A practical means of making the information available to the rotorcraft technical community should be prepared.

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B. GRAPHS AND FIGURES

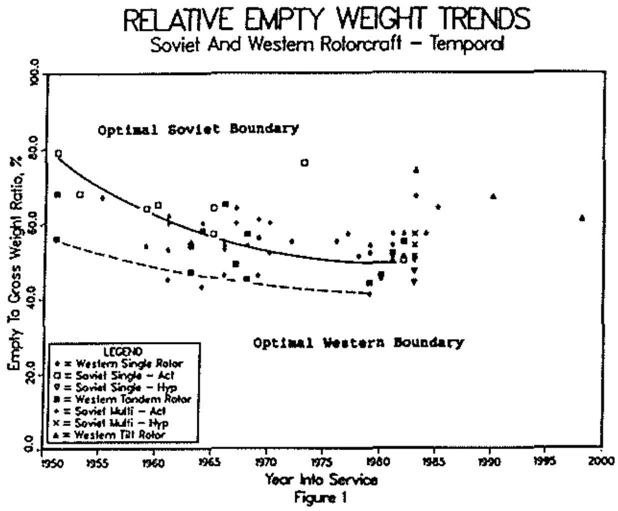


Figure 1

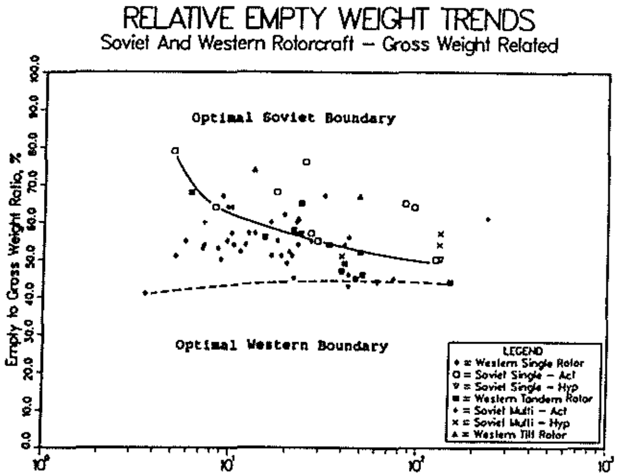


Figure 2

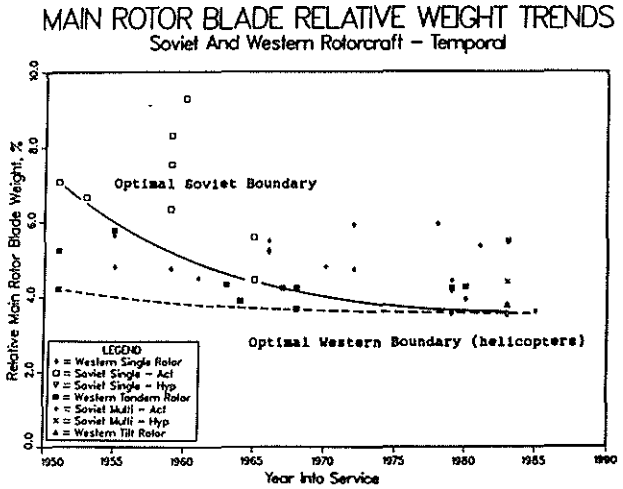


Figure 3

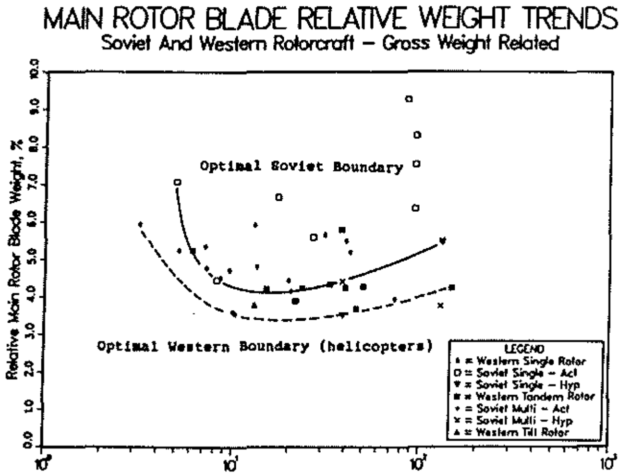


Figure 4

MAIN HUB & HINGE RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Temporal

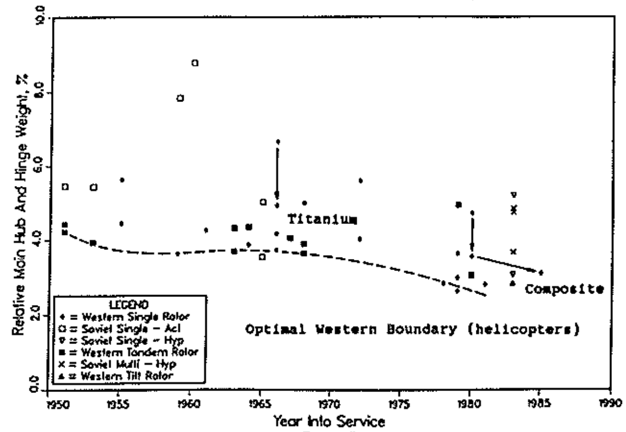


Figure 5

MAIN HUB & HINGE RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Gross Weight Related

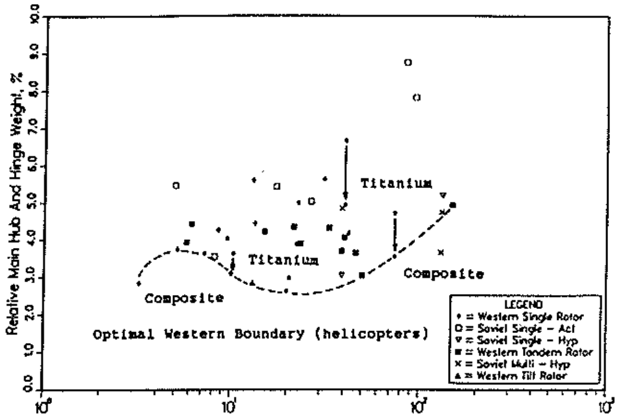


Figure 6

FUSELAGE RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Temporal

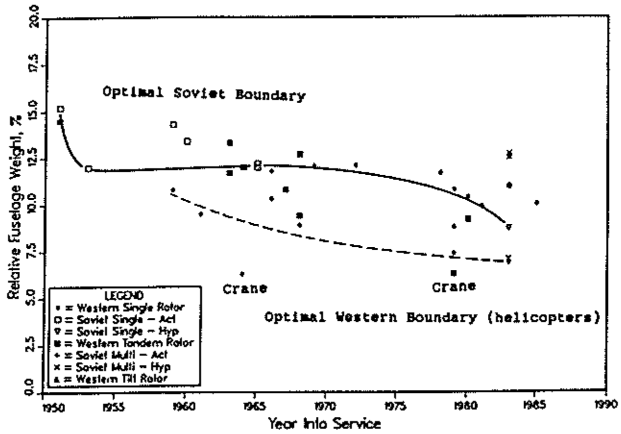


Figure 7

FUSELAGE RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Gross Weight Related

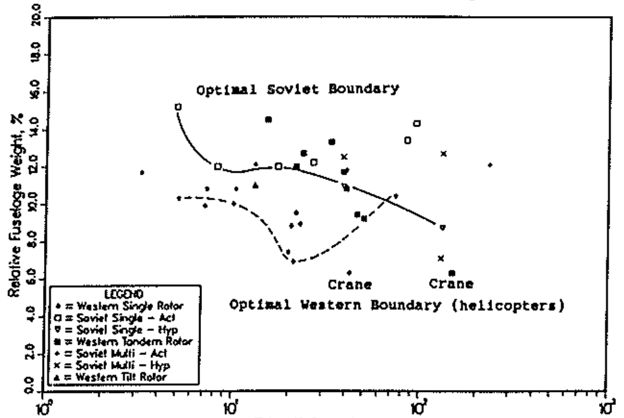


Figure 8

LANDING GEAR RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Temporal

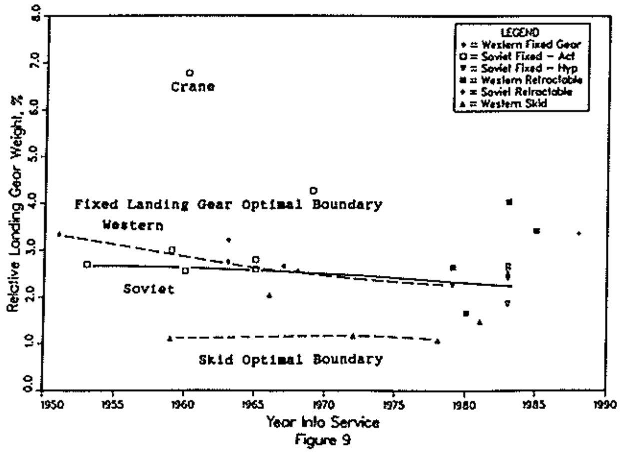


Figure 9

LANDING GEAR RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Gross Weight Related

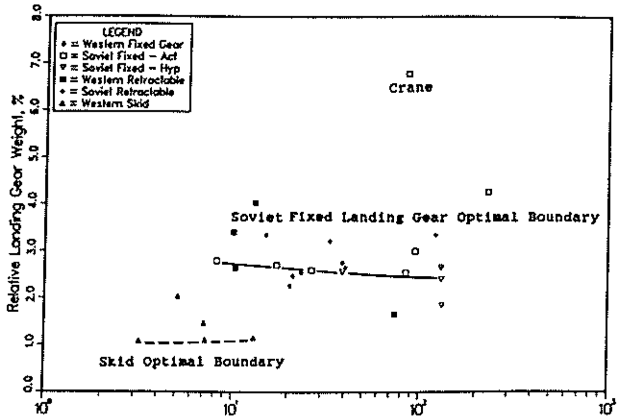


Figure 10

DRIVE SYSTEM RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Temporal

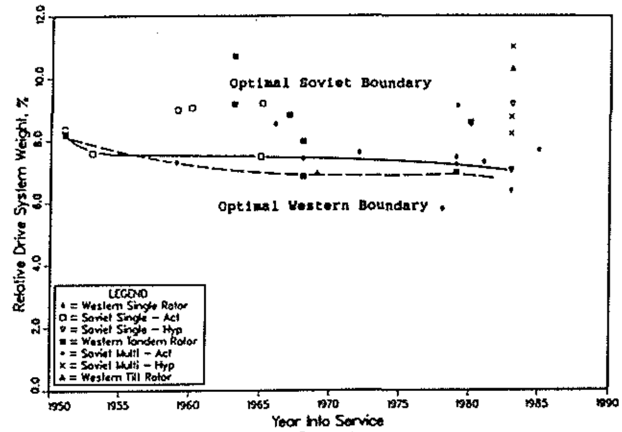


Figure 11

DRIVE SYSTEM RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Gross Weight Related

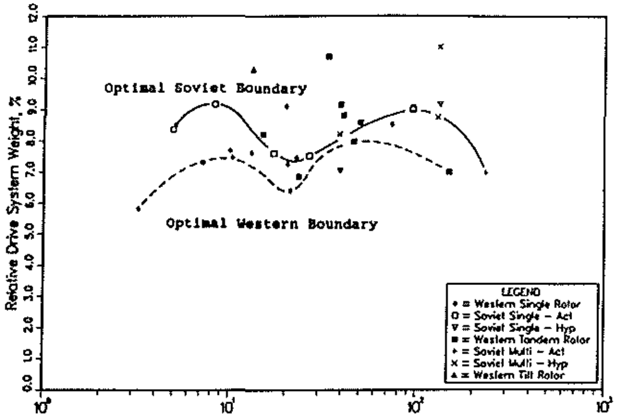


Figure 12

FUEL SYSTEM RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Temporal

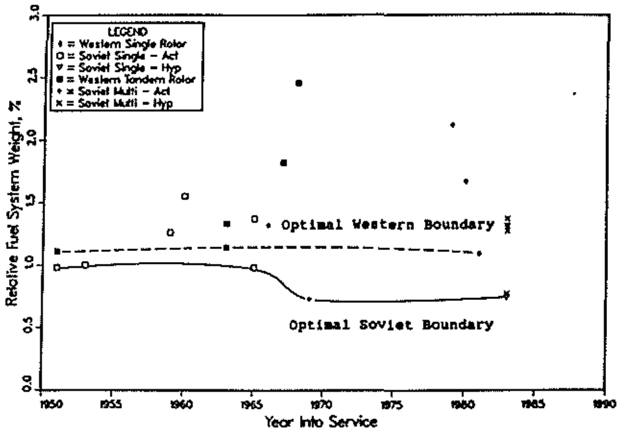


Figure 13

FUEL SYSTEM RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Gross Weight Related

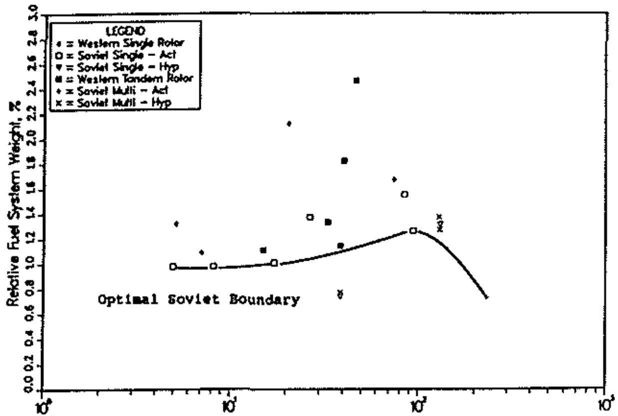


Figure 14

FLIGHT CONTROLS RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Temporal

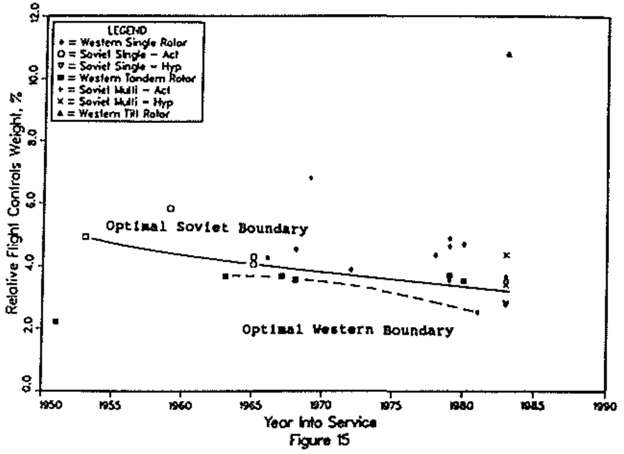


Figure 15

FLIGHT CONTROLS RELATIVE WEIGHT TRENDS
Soviet And Western Rotorcraft – Gross Weight Related

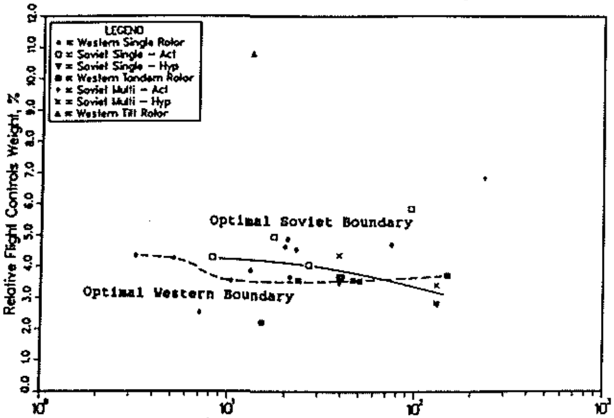
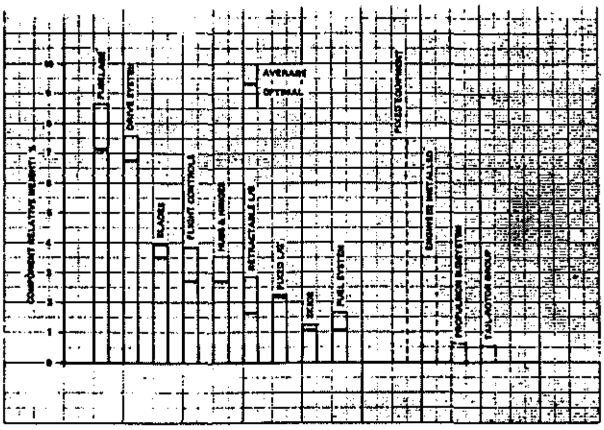


Figure 16



Average and optimal relative weights of major components for Western helicopters of the eighties

Figure 17

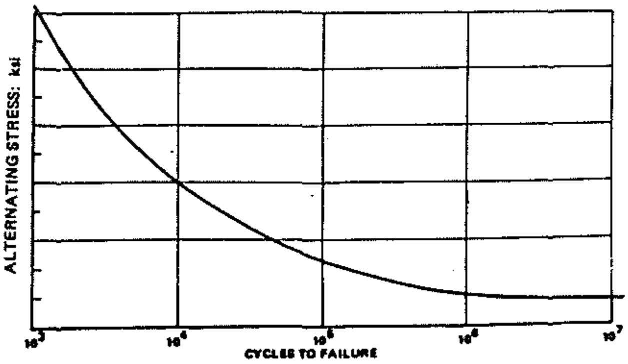
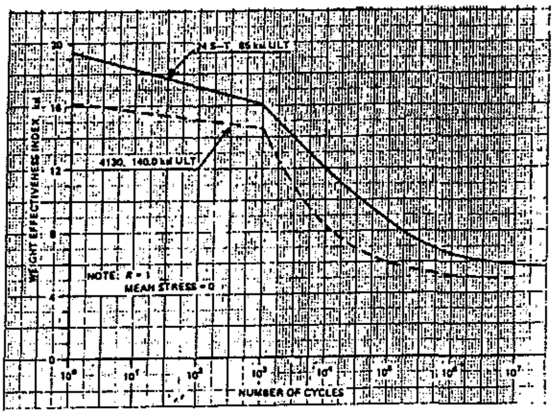
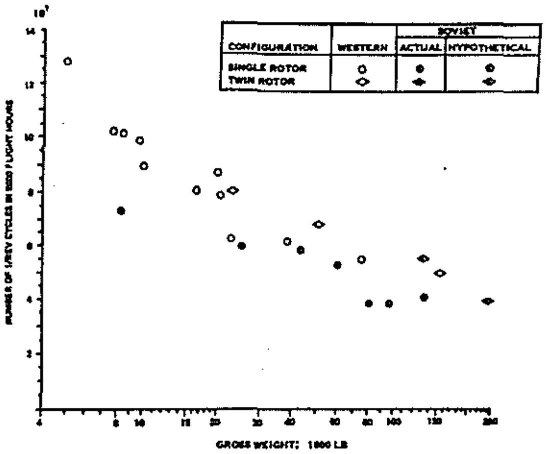


Figure 18



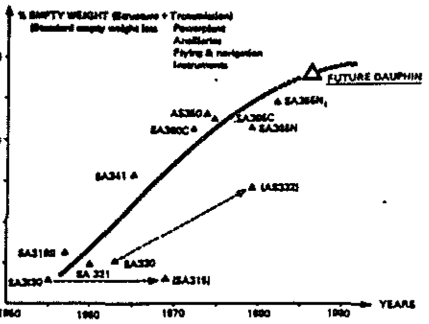
Example of weight effectiveness indices for aluminum alloy and steel under fatigue conditions

Figure 19



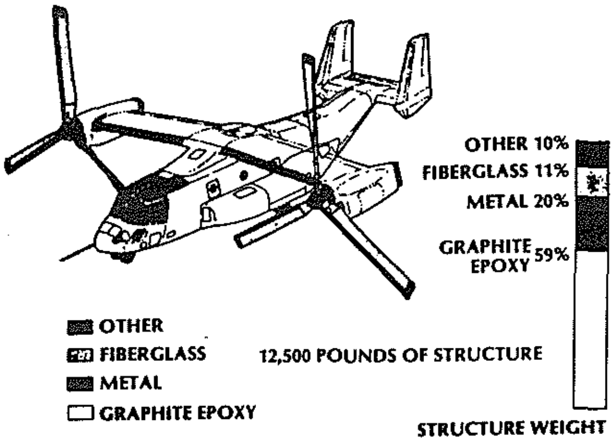
Total number of 1/rev cycles experienced by helicopters of various gross-weight classes during 5000 hours of normal operation

Figure 20



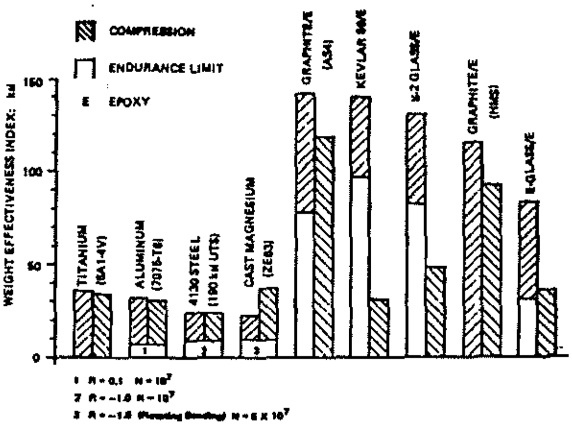
Past and future growth in application of composites to helicopters

Figure 21



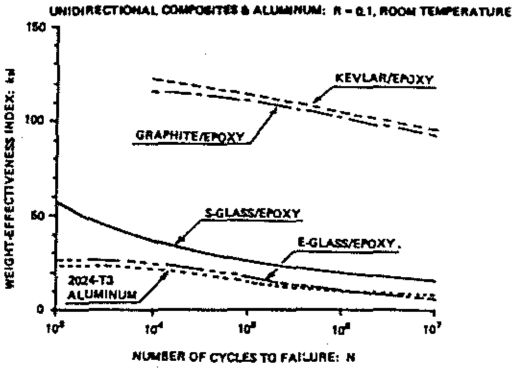
V-22 Material Applications

Figure 22



Example of bar-chart presentation of weight-effectiveness indices

Figure 23



Weight-effectiveness indices for fatigue conditions

Figure 24