# MATERIAL SELECTION FOR AERONAUTICAL STRUCTURAL APPLICATION

JÚLIO C. O. LOPES

Instituto de Logística da Aeronáutica, Subdivisão de Ensino Presencial,
Av. Monteiro Lobato 6365, Cumbica, Guarulhos,São Paulo
julio_inb@hotmail.com

**ABSTRACT:** The use of different materials as metals, wood and other modern materials like composites, require a previous evaluation of its performance under corrosion, creep, tension, compression, bending and fatigue. In general, these requirements lead to a few number of materials to choose during the project of one component, but in some cases, there's a lot of options that can be selected. In this work, a mechanical approach is considered for some classes of materials. Of course, a complete analysis involves a *management science*, also called, *operational research*, with an application of linear programming or, in some cases, heuristics models like *ants colony*, but this isn't our target at this moment. It's possible to see, with the mechanical approach, the advantage of composites materials application.

**Keywords:** *material selection, aeronautical materials*

**RESUMO:** O uso de diferentes materiais tais como metais, madeira e outros materiais modernos tais como os compósitos, requer uma avaliação prévia do seu desempenho e resistência à corrosão, fluência, tensão, compressão, dobragem e fadiga. Em geral, estes requisitos levam à escolha de uns tantos materiais durante o projecto de um componente, mas nalguns casos as opções possíveis são numerosas. Neste trabalho, é feita uma abordagem mecânica para algumas classes de materiais. Claro que uma análise completa envolve uma *investigação operacional*, com aplicação de uma programação linear e, nalguns casos modelos heurísticos como *colónia de formigas*, mas este não é o nosso objectivo neste momento. Com a abordagem mecânica, é possível ver a vantagem da aplicação dos materiais compósitos.

**Palavras-chave:** *selecção de materiais, materiais aeronáuticos*

## 1. INTRODUCTION

Some important factors have been considered during the selection of a material for aeronautical application. This material is submitted a various environments conditions like humidity, temperature and submitted under different types of mechanical solicitations like tension, compression, bending, cyclical forces, creep and torsion.

Nowadays, a lot of materials are available and it's difficult to choose the better solution because there are too many variables involved, and the cost is also an important factor to make a good decision.

In aeronautical applications, strength allied to lightness is most important in material selection, when the material is stable in environment conditions. In the majority of situations, trials and errors could be very expansive and a good project and design is necessary.

For the reasons mentioned above, the materials properties must be considered for structural application as:

- Ultimate stress
- Yield stress
- Stiffness (modulus of elasticity )
- Temperature limits
- Corrosion resistance (hostile environment)
- Fatigue resistance (Stress-Number fatigue curve)
- Fracture toughness
- Fragility at low temperatures
- Crack growth resistance
- Ductility
- Maintainability ( time for inspections, repair …)
- Reliability ( medium time between fail … )
- Fabricability

The main group of materials used in aircraft construction has been:

- wood
- steel
- aluminum alloys
- titanium alloys
- fiber reinforced composites

## 2. WOOD

The first aircraft were constructed from wood (spruce and birch) covered with canvas. Wood has a good strength/weight ratio about 0.1 same as aluminum alloys. Major disadvantages of the wood are: moisture absorption and anisotropy caused by grain structure. During WWII there was shortage of factories and skilled workers for metal fabrication whereas furniture industry helped. This is the reason of Soviets success, because Germans had all-metal structures. It must be admitted, that special circumstances of the time were the reason of it.

## 3. ALUMINUM ALLOYS

Since 1920, aluminum alloys have been the mostly used material in airframe construction. Nowadays, there are a lot of aluminum alloys with very similar proprieties. So, which factor is most important to choose an alloy?
As usual, when one propriety is improved, other on is sacrificed. The 2024 alloy has lower ultimate stress compared with 7075 alloy in the aged condition, but with better fatigue proprieties. This is the reason why 7075 is used for upper surface and 2024 is used for lower surface in Tupolev-154. For the lower surface, the fatigue proprieties are more important, due the tensile loads that predominate most of the time.
In some applications, corrosion resistance of an aluminum alloy has been improved by a layer of pure aluminum. The aluminum alloys have worst corrosion resistance than commercial pure aluminum. This "sandwich" is called Alclad.

## 3. STEEL ALLOYS

Steel are applied in various components in an aircraft. Mig-25 is an example of aircraft with all structural components made with steel. In the end of 60's years, during the cold war, URSS made an aircraft that was possible to reach Mach 3 (in 1973, over Israel, one Mig-25 reach 3.2. The practical limit was 2.8 due turbine problems). In this condition, the surface temperature is almost 300$^o$C, due the air friction and, for this reason, aluminum alloys wasn't applied.
Steel based in iron-nickel (Maraging steel) was the better solution. With an aircraft based in steel alloys, the weight was 29 ton.
High specific weight of the steels prevented from wide use in aircraft construction. But steel is used for highly stressed components such as undercarriage, control surface tracks, fasteners (bolts), wing and tail to fuselage attachments.
While steel has a high strength it is difficult to manufacture. To overcome some of these difficulties, Maraging steel were invented in which carbon is eliminated and elements like Co, Mo and Ti were added. Maraging steel has excellent yield, ultimate stress and impact resistance (associated with other advantages). Maraging steel have been used, normally, as: aircraft arrest hooks, rocket motor cases and landing gears.
Stainless steels are used to resist kinetic heating in super or hypersonic experimental rocket aircraft X-15.
SR-71 was made mostly of titanium. This aircraft was developed for special proposes, like a spy aircraft.

## 4. TITANIUM ALLOYS

Titanium was used in Concorde and SR-71 airframes. Titanium has an excellent relation stress/weight, good resistance to corrosion and good creep proprieties. Titanium is a very expansive alloy, compared with steel, and its uses is limited for special proposes. In turbines, titanium is used mainly due the temperature resistance (creep), low weight and corrosion resistance. After the combustion of the fuel, the temperature increases and Titanium alloys have been substituted by nickel alloys (super alloys). But in all situations the mechanical proprieties is important.

## 5. TYPES OF LOADING

Some important types of loading in structural material are:

- Tension
- Compression ( with two failure modes: yielding and buckling )
- Bending
- Torsion

The minimum weight of the aircraft is the most frequent factor to consider. Analyzing a structural component with a rectangular section ( t x h ) and with a length L as show in figure 1, it's possible to show that:

V = L.t.h (1) , W= □.L.t.h (2) and A = t.h (3)
where V=volume W=weight A=area and □=density
$I = th^3/12$ (4) where I = inertia moment
From (2) we have that t.h = W/(□.L) and $t^3.h^3 = W^3/(□.L)^3$ (5)
Using (5) in (4) ;
$I = t^3h^3/(t^2.12) = A^3/(t^2.12)$ (6) or $W^3/(12.t^2.□^3.L^3)$ (7)

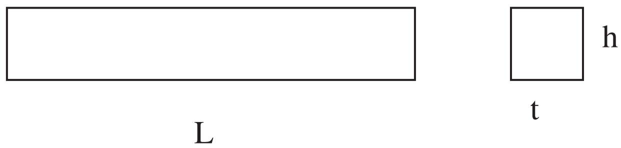


**Fig. 1**. Dimensions of component analyzed

### 5.1 Tension [1]

Under a certain load (F) until the yield limit is reached, the applied stress is:

$□_y$ = F/A and from (2) and (3) A = W/(□.L)

Therefore:

$□_y$ = F.□.L/ W or W= F.□.L/$□_y$

The interest here is to compare two different materials called (a) and (b), and there are two expressions:

$W_{(a)}$ = F.$□_{(a)}$.L/ $□_{y(a)}$
$W_{(b)}$ = F.$□_{(b)}$.L/ $□_{y(b)}$

The relation between these two different materials is:

$$\frac{W_{(a)} = F.□_{(a)}.L.□_{y(b)}}{W_{(b)} = F.□_{(b)}.L.□_{y(a)}}$$

$$\frac{W_{(a)}}{W_{(b)}} = \frac{\rho_{(a)}\sigma_{y(b)}}{\rho_{(b)}\sigma_{y(a)}}$$

### 5.2 Compression[1]

Analyzing failure due to buckling

□$_y$ = F/A = □$^2$.E.I / (A.L$^2$)  where E is the Elastic modulus
But I= A$^3$/(12.t$^2$) equation (6) so,
□$_y$ = F/A = □$^2$.E. A$^3$ / (12. t$^2$.A.L$^2$)

$$F = \frac{\pi^2 E A^3}{12 t^2 L^2} \quad \text{and} \quad A^3 = \frac{W^3}{\rho^3 L^3} \quad \text{so}$$

$$F = \frac{\pi^2 E W^3}{12 t^2 L^2 \rho^3 L^3} \quad \text{or} \quad W = \sqrt[3]{\frac{12 F t^2 L^5 \rho^3}{\pi^2 E}}$$

And finally, comparing two different materials (a) and (b):

$$\frac{W_{(a)}}{W_{(b)}} = \frac{\sqrt[3]{\dfrac{12 F t^2 L^5 \rho_{(a)}{}^3}{\pi^2 E_{(a)}}}}{\sqrt[3]{\dfrac{12 F t^2 L^5 \rho_{(b)}{}^3}{\pi^2 E_{(b)}}}} =$$

$$= \frac{W_{(a)}}{W_{(b)}} = \sqrt[3]{\frac{12 F t^2 L^5 \rho_{(a)}{}^3 E_{(b)}}{12 F t^2 L^5 \rho_{(b)}{}^3 E_{(a)}}} = \frac{\rho_{(a)}}{\rho_{(b)}} \sqrt[3]{\frac{E_{(b)}}{E_{(a)}}}$$

$$\frac{W_{(a)}}{W_{(b)}} = \frac{\rho_{(a)}}{\rho_{(b)}} \sqrt[3]{\frac{E_{(b)}}{E_{(a)}}}$$

### 5.3 Bending[1]

The expression for the tension1 is:

$$\sigma_y = \frac{Mh}{2I} \quad \text{using the equation (4) } I = th^3/12$$

$$\sigma_y = \frac{12Mh}{2th^3} = \frac{6M}{th^2} \quad \text{and} \quad \sigma_y = \frac{6M}{th^2} \cdot \frac{t}{t} = \frac{6tM}{t^2 h^2}$$

But A$^2$=t$^2$h$^2$ and W$^2$=□$^2$L$^2$A$^2$  so

$$\sigma_y = \frac{6tM}{t^2 h^2} = \frac{6tM \rho^2 L^2}{W^2} \quad \text{and finally:}$$

$$W = \sqrt{\frac{6tM\rho^2 L^2}{\sigma_y}} = \rho L \sqrt{\frac{6tM}{\sigma_y}}$$

Comparing two different materials:

$$\frac{W(a)}{W(b)} = \frac{\rho(a) \dfrac{\sqrt{6tM}}{\sqrt{\sigma_{y(a)}}}}{\rho(b) \dfrac{\sqrt{6tM}}{\sqrt{\sigma_{y(b)}}}} = \frac{\rho(a)}{\rho(b)} \frac{\sqrt{\sigma_{y(b)}}}{\sqrt{\sigma y_{(a)}}}$$

### 5.4 Torsion[1]

For torsion analysis, a circular section is to much easer for compare. In this case, a circular section with a D diameter is considered.
The torsion T applied on this tube is resulted by a force F. T= F * D/2, and the shearing produced is:

$$\tau_{\max} = \frac{8F}{\pi D^2} \quad \text{but here W=□.L.A and} \quad A = \frac{\pi D^2}{4} \quad \text{, so}$$

$$W = \rho \frac{L \pi D^2}{4} \quad \text{and} \quad D^2 = \frac{4W}{\rho L \pi}$$

And $\tau = \dfrac{2F\rho L}{W}$ finally $W = \dfrac{2F\rho L}{\tau}$

The relation between two different materials is:

$$\frac{W_{(a)}}{W_{(b)}} = \frac{\rho_{(a)} \tau_{(b)}}{\rho_{(b)} \tau_{(a)}}$$

## 6. RESULTS

To compare different materials, the aluminum 2024 was considered as alloy for reference (material(b)), and the others materials was considered as material (a), to calculate the relations between the weight. Table 1 shows some figures for 10 materials. [2]

**Table 1 - Typical figures for structural aeronautical materials**

| class of material | Material | density (kg/m3) | □y (Mpa) | Elastic Modulus (Gpa) | Elongation % | Temperature limite oC | Cost $/lb |
|---|---|---|---|---|---|---|---|
| aluminum (reference) | 2024 T3 | 2800 | 510 | 72.5 | 10 | 280 | 3 |
| aluminum | 7075 T6 | 2800 | 586 | 71.7 | 4 | 250 | 3 |
| maraging steel | C-250 | 7920 | 1620 | 183 | 5 | 1000 | 5 |
| steel | 4340 | 7830 | 1900 | 170 | 11 | 1100 | 1 |
| titanium | 8Al-1Mo-1V | 4370 | 1000 | 121 | 8 | 800 | 15 |
| wood | spruce | 560 | 67.5 | 14.5 | 0 | 200 | 2 |
| composites | glass-epoxi | 1960 | 730 | 44.6 | 0 | 350 | 2.9 |
| composites | graphite-epoxi | 1540 | 1080 | 312 | 0 | 350 | 32 |
| composites | Boron-Aluminum | 2800 | 840 | 241 | 0 | 600 | 320 |
| composites | | | | | | | |

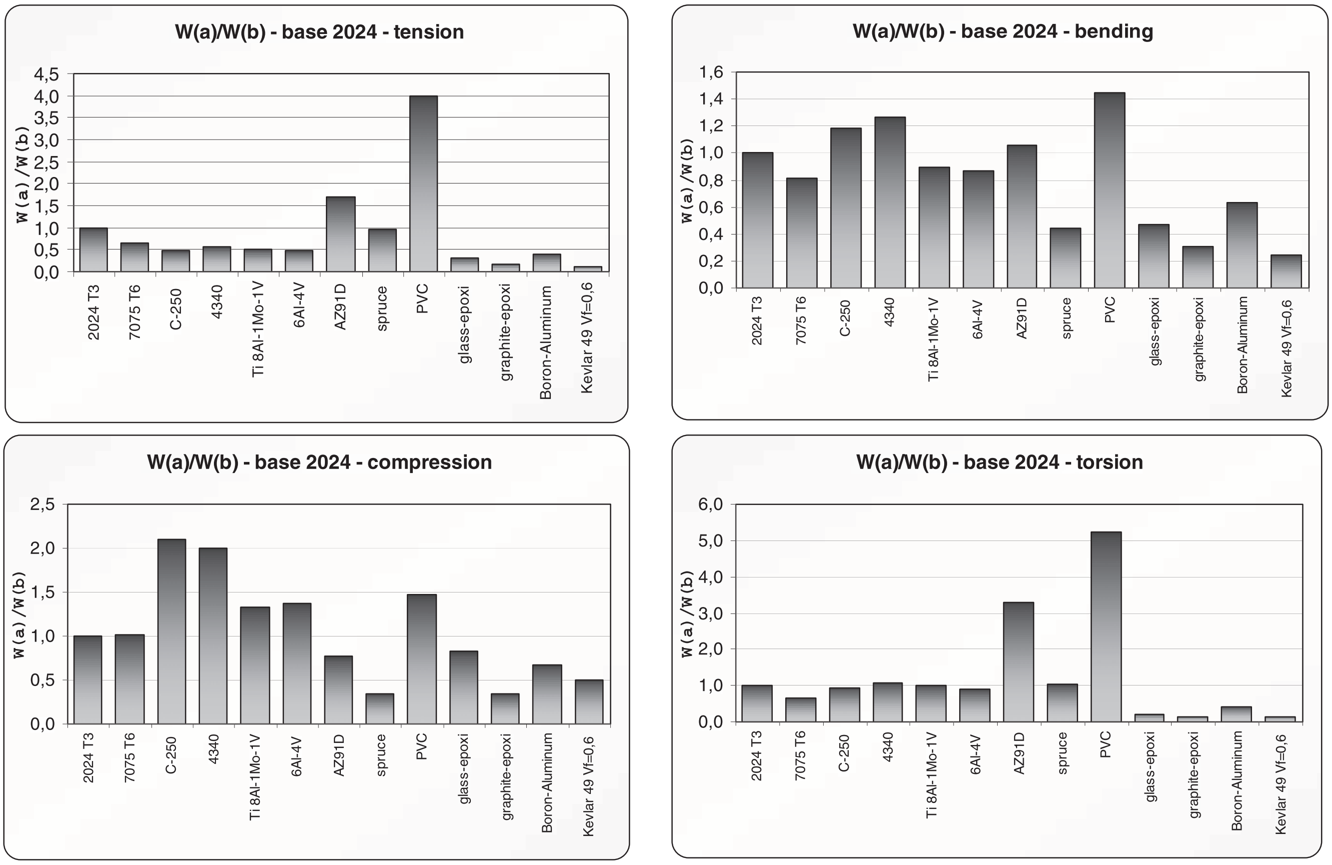


**Fig. 2**. Analysis of weight for various types of material

For military applications, the weight is the most important driver for material selection, but for commercial applications, the cost must be considered. The analysis of the material cost, involves the product between specific cost and the weight. The relative cost between the material (b) and the aluminum 2024 was considered, and this cost factor was multiplied by the weight relations. The result is showed in figure 3.

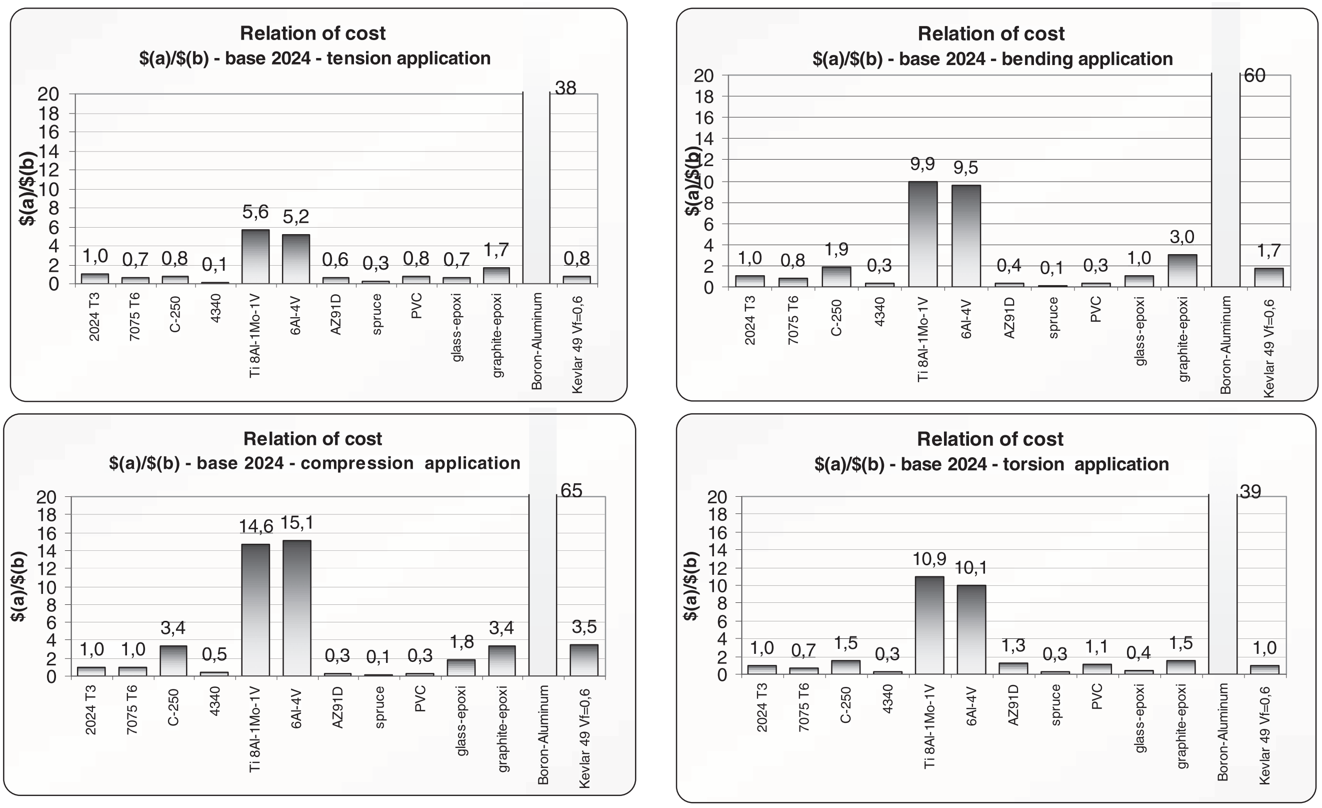


**Fig. 3.** Relation of costs in different types of loading

## 7. CONCLUSIONS

With the development of technology in the real world, the options of material for aeronautical application grow every day and there are a lot of options to choose.

The engineer sometimes has made a decision based on the "tradition" or in the point of view of standards.

When we think in the weight of an aircraft, composites materials seems to be the most interested material, for all types of loads, including tension, compression, bending or torsion, but in this case, the cost should be too high for commercial applications. So, for military applications, where the weight is very important with the cost as a secondary factor, the composites materials have a promised future.

For commercial aircrafts, the cost is the most important factor to be considered. The weight has, in this case, a secondary importance. Metals and alloys like, aluminum, steel and magnesium are preferred, as show in figure 3. Unfortunately, wood and PVC have a lot of restriction for application like humidity and temperature.

This question of material selection is difficult to solve and the tendency is to use computer models. New materials have a promised future, and the price for composites has a tendency to decrease becoming a good alternative in the future.

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