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Dr. Ahad Armin

Design of a Fan Blade for an Aircraft Turbine Engine

By:
Christopher Dherman

Nathan Cushing

Emi Cigarroa Aguilar

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Abstract

This paper discusses the several design criteria that need to be considered during the selection process of an appropriate material for a blade of an aircraft turbine engine. It is explained how safety is the largest determining factor for most of the design criteria. Several mechanical properties regarding the safety of the appropriate material for the blade are explained and compared for different materials. The best-overall material of Carbon Fiber Reinforced Composites was accordingly with an appropriate justification for our selection.

Introduction

In all industries, such as the manufacturing or consumer goods industries, the design and creation of a product involves several processes that are ultimately determined by manifold factors that constrain the final product to serve a specific purpose. Some of the factors that companies often consider are such as production costs, safety, environmental impact, lifespan, etc. These factors can vary widely depending on the desired purpose that the product must fulfill. For example, when designing a road bike, to ensure that the bike can be ridden the manufacturer must consider things like the strength of the material they're using, its durability, and its safety under repeated use. Another example could be the design of a toy for toddlers. In this case, the manufacturer would have to make sure that the toy is made with a material that is safe for daily use, chemically inert, and regarding the design aspect, it shouldn't have any sharp corners. From these examples we can see that the factors regarding the design aspect of a product are notably different for each case. Ultimately, one of the most important choices that must be made during the design process is selecting an appropriate material, as this will often determine a lot, if not most of the design criteria. This is why we will put our focus into discussing how different design parameters affect the selection criteria for a real-life example: A blade for an aircraft turbine engine.

When selecting an appropriate material for the blade of a turbine engine, safety is the most important design aspect that we need to keep in mind. Products that are often intended for commercial use often place a lot of emphasis on their safety. Especially in this example where the stakes are exceedingly high. If we were to select an unfit material, if the blade were to fail amidst a commercial flight, it could lead to several fatalities. This is why although there are several design criteria to be kept in mind, we will dedicate most of the discussion to explaining the different safety requirements that *must* be met in order to consider the blade as safe. The final selection process will then be performed with the aid of Granta Edupack simulation software, which will provide helpful insights by sorting and filtering the materials from its database and leaving in only the materials that meet and/or exceed our criteria. Without further ado, the following pages will go in-depth regarding each of the design criteria.

Design Considerations and Safety Constraints

General design considerations

The following table provides a brief overview of the several design parameters that will be considered for our material selection process.

Constraint	Numerical	Notes
Tensile Stress	$\frac{\sigma}{\rho} \geq 0.11$	**Must** meet or exceed
Thermal Conditions	Avg. Max Service Temperature $\geq 100°C$	**Must** meet or exceed
Fracture Toughness	$\frac{K}{\rho} \geq 4.3596 \cdot 10^{-3}$	**Must** meet or exceed
Fatigue Strength	$\frac{\sigma_u}{\rho} > 0.22$	**Must** meet or exceed
Vibrational Fatigue	$(\frac{E}{\rho})^{\frac{1}{2}}$	High as possible
Material and Fabrication Cost	-------	Keep low

Fundamental requirements

We are considering six safety constraints in total, for which three of them will be considered our *fundamental constraints*. Based on the explanation given in the problem statement, we are considering six safety constraints for the selection criteria. Four of these constraints must absolutely be met to consider the selected material as safe. However, these can be reduced down to three constraints since fatigue strength and tensile strength are the same metric, but fatigue strength requirements are simply more stringent.

These three constraints are 1) service temperature, 2) fatigue strength and 3) fracture toughness and will be appropriately named as the *fundamental constraints* or *fundamental requirements* for the material selection criteria. The remaining safety constraints do not impose a requirement that must be met but instead they are factors that should be considered during the material selection process only once these materials have already passed the fundamental requirements. Thus, in this section we will first briefly mention the theory behind each fundamental constraint and then discuss the five materials that passed the first selection stage by meeting or exceeding the fundamental requirements. We will consider the remaining safety constraints thereafter.

Thermal Conditions

Because the blades of the turbine engine operate at very high temperatures, we need to consider a material has a service temperature above 100 ℃. If the material chosen had a lower service temperature, it could lead to mechanical failure or other undesired problems such as combustion, warping or melting.

While this temperature may seem low for a jet engine, in the high bypass turbofan engine that is targeted, the first set of fan blades are well fore of the combustion chamber and begin the compression process with fresh air; these blades are subject to ambient air, and have much lower temperature requirements than the blades on the interior of the engine.

Tensile and Fatigue Strength

Tensile Strength and Fatigue Strength are important safety constraints to consider. To decide which material would fit our conditions to withstand the centrifugal loading the following formula was considered:

$$\sigma = 0.11\rho$$
$$\frac{\sigma}{\rho} = 0.11 \qquad (1)$$

According to the above equation, Tensile Strength (σ) over Density (ρ) should equal the coefficient (0.11). However, fatigue strength constraints indicate that the turbine blade needs to withstand constant load for at least 100 000 cycles, where each consists of one start-stop cycle. This criterion can be simplified by assuming the material can survive 100 000 cycles if the tensile stresses are held below half the ultimate tensile strength (σ_u).
Therefore, if the below condition is met, the material passes the fatigue strength and tensile strength requirement.

$$0.11 \cdot \rho < 0.5(\sigma_u)$$
$$\frac{\sigma_u}{\rho} > 0.22 \qquad (2)$$

Fracture Toughness

This is yet another basic and essential feature to keep in mind when designing the blade for a turbine engine. The fracture toughness of a material is defined as the measure of a material's resistance to undergo a brittle fracture when a crack is present. That is, the larger this value is for a specific material, it will resist fracture better. Suppose a commercial flight from British Columbia to Toronto is taking place, and as the plane travels along and above Canada's provinces, the fan blades in the turbine engines will often come across foreign objects such as rocks that could often cause a crack or dent in them. If the material used in the fabrication of these blades had a low fracture toughness, the crack caused by any sort of external factor would propagate quickly and fracture the blade. If the fan blades had otherwise a high fracture toughness, the crack could be sustained throughout the entire duration of the flight without causing a fracture and could be later examined after landing to assess the severity of the problem. This is why it is imperative to consider fracture toughness when selecting an appropriate material for the fan blades.

Mathematically, fracture toughness is defined as:

$$K = Y\sigma\sqrt{\pi a} \quad (3)$$

For which

- K is denoted as the material's fracture toughness or stress intensity factor
- Y is a dimensionless parameter in which for this case it is assumed to be 1
- σ is the maximum applied tensile stress present at or close to the crack or fracture
- a is the crack length expressed in m.

Therefore, from this equation we can see that the fracture toughness of a material depends on two parameters: the applied tensile stress and the length of the crack. However, it is explained in the problem statement that a 0.5 mm deep impact crack should not be able to propagate and lead to a fast fracture, and thus, a=0.5 mm can be set as the lower limit for fracture toughness and leave eq. (3) as a function of tensile stress (σ) only. Furthermore, following the previous conditions on the problem statement we see that the relationship between density and tensile strength due to the centrifugal forces of the blades is established as follows: $\sigma = 0.11\rho$. Thus, we can substitute this value into eq. (3):

$$K = \sigma\sqrt{\pi a} = 0.11\rho\sqrt{\pi a} \qquad (3.1)$$

Setting a=0.5 mm leads to the following linear relationship between fracture toughness and density:

$$K = 0.11\rho\sqrt{\pi(0.5 \cdot 10^{-3}\ m)} = 4.3596 \cdot 10^{-3}\rho \qquad (3.2)$$

And by rearranging variables:

$$\frac{K}{\rho} = 4.3596 \cdot 10^{-3} \qquad (3.2)$$

Materials that meet the Fundamental Requirements

Based on our simulation results using Granta EduPack, only five materials meet the fundamental requirements. These five materials are: Low-alloy steel, Titanium alloy, CFRP (Carbon Fiber Reinforced Composite), Wrought magnesium alloys and Bamboo. We will now discuss in-depth the differences between each of the five materials based on each fundamental requirement separately and draw a conclusion based on our findings. At the end, we will discuss and consider the remaining requirements to determine and select the best overall material.

Tensile and Fatigue Strength

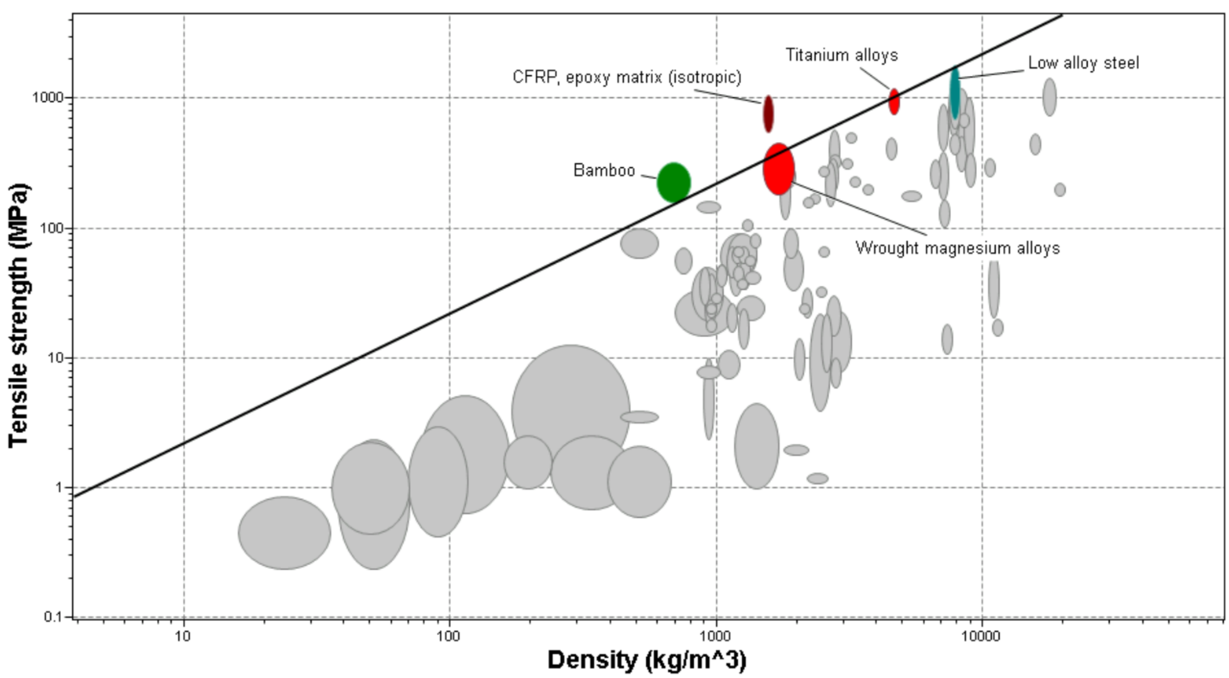


Figure 1: *Graph represents Tensile Strength against Density*

Plotting the graph Tensile strength (MPa) against Density ($\frac{kg}{m^3}$), we set a filter line to select materials that only meet the condition from equation (2). The following table is ranked according to these selected materials and their perpendicular distance from the filter line. (There longer the perpendicular distance the better).

Rank	Material	Ultimate Tensile Strength (σ_u)[MPa]	Density (ρ)[$\frac{kg}{m^3}$]	Fatigue strength Coefficient
1	CFRP, Epoxy Matrix	1.05e3	1.55e3	0.68
2	Bamboo	319	693	0.46
4	Wrought magnesium alloys	450	1.17e3	0.38
2	Titanuim Alloy	1.19e3	4.61e3	0.26
5	Low alloy steel	1.80e3	7.80e3	0.23

Table 1: *Materials that passed Tensile and Fatigue Strength test.*

Thermal Conditions

To determine the appropriate thermal conditions, the maximum service temperature of the materials was plotted together, with a line showing the cutoff point of 100℃. As shown in Figure 2, the 5 selected materials passed this thermal condition.

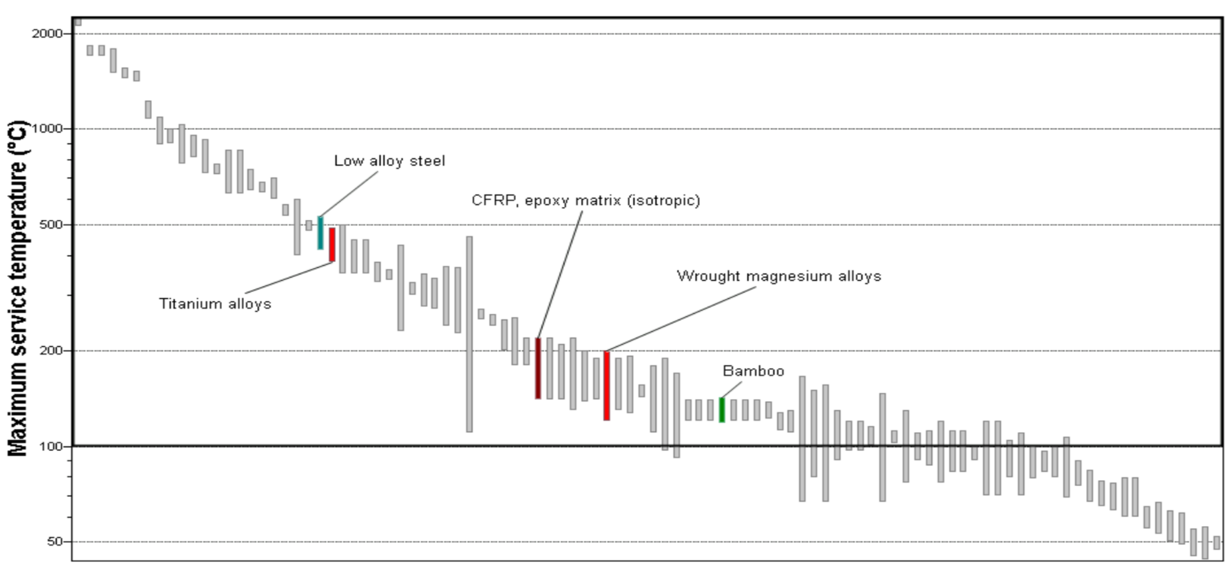


Figure 2: *Graph of Material Max Service Temperatures*

Rank	Material	Range of Max Service Temperature (°C)
1	Low Alloy Steel	415-530
2	Titanium Alloy	380-487
3	CFRP, Epoxy Matrix	140-220
4	Wrought magnesium alloys	120-200
5	Bamboo	118-142

Table 2: *Results of selected materials in order of highest service temperatures*

Fracture Toughness

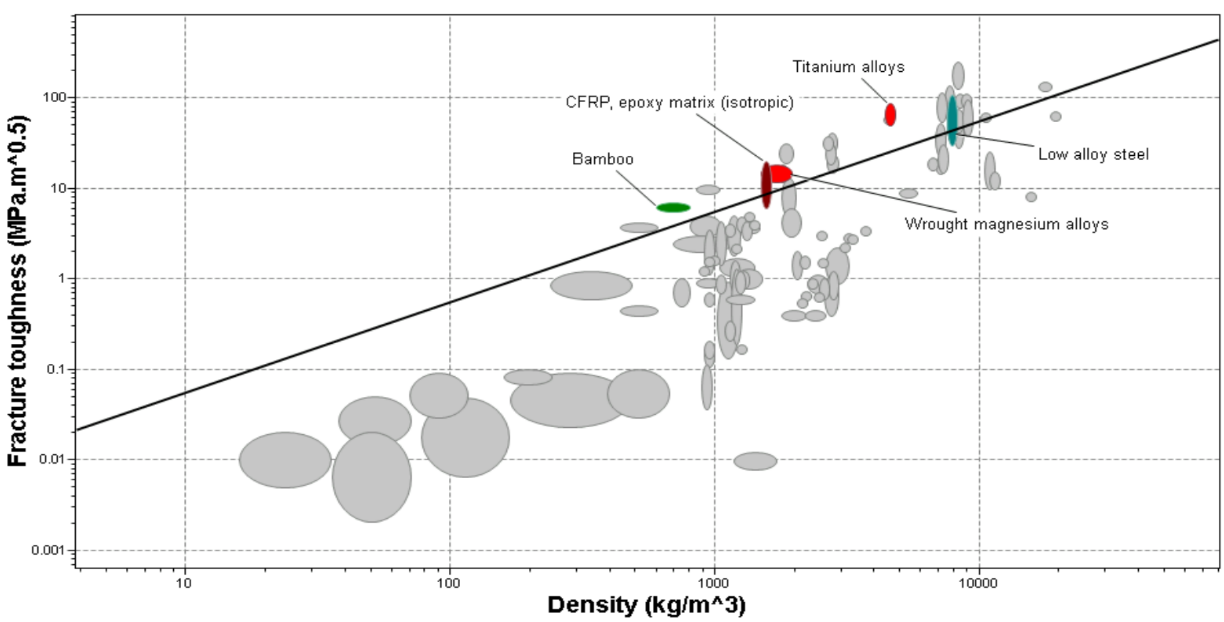


Figure 3: Graph of Fracture toughness against Density

In this case, any material lying above the line can withstand a 0.5 mm fracture without causing the crack to propagate rapidly. The rankings of these materials based on fracture toughness/density are as follows.

Rank	**Material**	**Fracture strength** (Mpa$\sqrt{m}$) **(range)**	**Density** (kg/m^3) **(range)**	**Fracture strength/Density** (Mpa$\sqrt{m}$)/ (kg/m^3) (midpoint)
1	Titanium Alloy	51.3-86.1	4.43e3-4.79e3	1.49e-2
2	Bamboo	5.69-7.01	602-797	9.08e-3
3	Low Alloy Steel	30-106	7.8e3	8.72e-3
4	Wrought Magnesium Alloys	12-18	1.5e3-1.95e3	8.70e-3
5	CFRP, Epoxy Matrix	6.12-20	1.5e3-1.6e3	6.06e-3

Table 3: *Results of selected materials in order of highest Fracture Strength/Density*

We see that a common trend is that materials with the highest fracture toughness are most often metal alloys or metals that have undergone treatments such as stainless steel or low alloy steel. However, density also plays a huge role in material selection. As the fracture strength/density is what is needed, not the absolute fracture strength.

Both the table and the graph give the rankings of the five materials based on their fracture strength to density ratio (this is visually represented in Figure 3 by the material's perpendicular distance to the cutoff line). It is worth noting that the titanium alloy took the top place whereas bamboo took the second highest; at a first glance and when comparing the mechanical properties of these materials, we see that although these materials are completely different they still provide good amounts of fracture toughnes/density. This dichotomy can be explained by realizing that on one hand, the titanium alloy has excellent mechanical properties at the cost of being very dense, whereas bamboo provides lackluster mechanical properties at the benefit of being much lighter. This is why although bamboo may seem like an odd choice of a material for the design of a turbine engine blade, only because of the nature of the problem and the importance of the density of the selected material, the relationship between the mechanical properties and density of bamboo constitutes a surprising candidate.

Non-fundamental requirements

Vibrational Fatigue

Another important consideration is vibrations. The blades can be modeled as a second order system, in which case the natural frequency will scale with $(\frac{E}{\rho})^{\frac{1}{2}}$. The natural frequency is where the response to a system at a given force is proportionally the greatest. When plotting a bode plot of a second order system, there is a relatively flat gain, then a rise up to a maximum point, fllowed by a steady state gain decline. This maximum point should be shifted as far to the right of the Bode plot, or in other words, increase $(\frac{E}{\rho})^{\frac{1}{2}}$, so that frequencies in this system are less likely to get amplified the maximum amount. Fig 4 shows various materials plotted against $(\frac{E}{\rho})^{\frac{1}{2}}$.

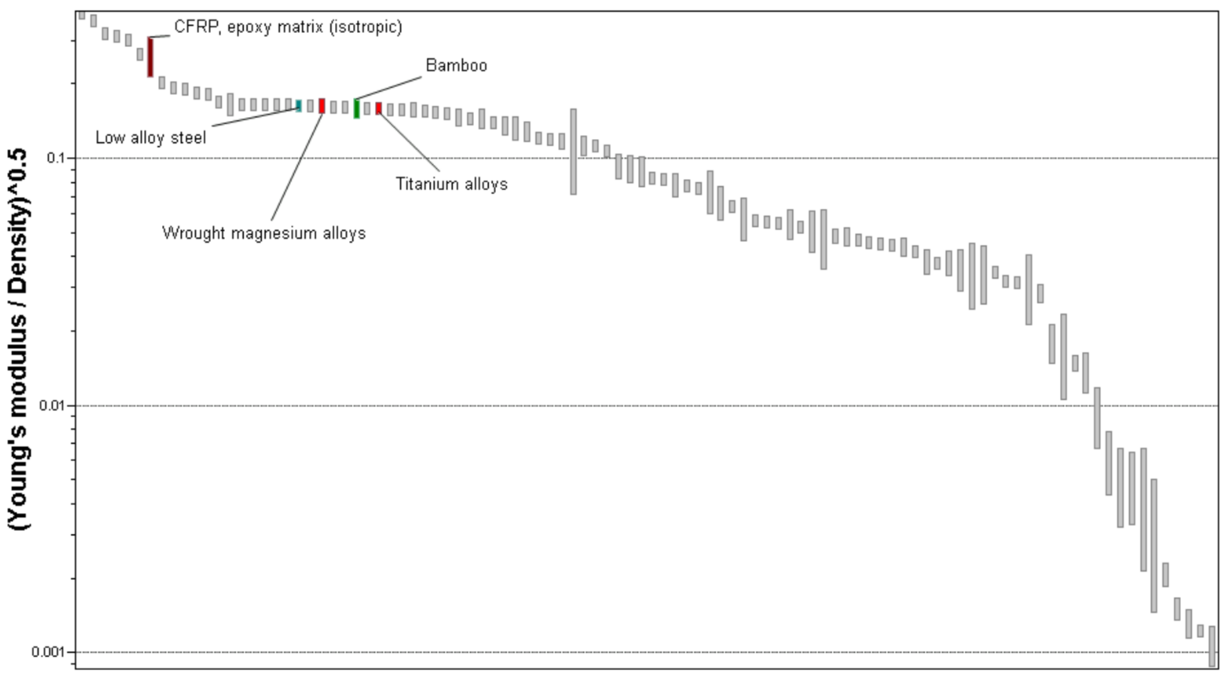


Figure 4: (Young’s modulus/Density)^0.5

Rank	**Material**	**Young’s Modulus** (Mpa) **(range)**	**Density** (kg/m^3) **(range)**	**Young’s Modulus/Density** (MPa)/ (kg/m^3) (midpoint)
1	CFRP, Epoxy Matrix	6.9e4-1.5e5	1.5e3-1.6e3	70.65

2	Low Alloy Steel	2e5-2.1e5	7.8e3	26.3
3	Wrought Magnesium Alloys	4.2e4-4.7e4	1.5e3-1.95e3	25.80
4	Bamboo	1.51e4-1.99e4	602-797	25.02
5	Titanium Alloy	1.1e5-1.2e5	4.43e3-4.79e3	24.95

Table 4: *Results of selected materials in order of (Young's modulus/Density)^0.5*

From this, it is clear that CFRP is the has the best vibrational performance by far, with the other 4 materials having similar performance to each other.

Material and Fabrication Costs

In this section we consider the cost of material as well as how much it will cost to fabricate such materials. The main objection of this constraint is to minimize cost possible as in previous sections we have focused on safety aspects. Therefore, knowing that we have accounted for safety conditions we can solely focus on reducing costs.

We are able to achieve this by first calculating the volume of turbine blade. Given the following specific dimensions:

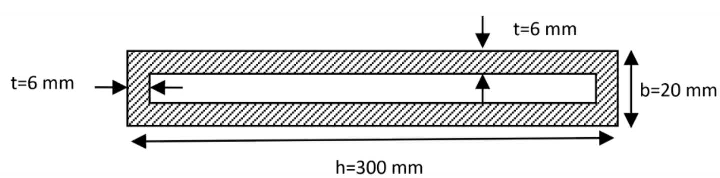


Figure 1. Cross section of the designed cavity inside fan blades (not scaled)

$$\begin{aligned} Volume_{Balde} &= Volume_{Outter} - Volume_{Inner} \\ &= 0.0054[m^3] - 0.0020736[m^3] \\ &= 3.3264 \ \cdot 10^{-3}[m^3] \end{aligned}$$

Knowing the volume of our turbine blade, we then choose the material we are interested in and takes its density multiplied by the constant volume of our blade to find the mass of the blade according to the chosen material's density.

Rank	Material	Density(ρ)[$\frac{kg}{m^3}$]	Mass(kg)	CAD($)/ kg	Material Cost per Blade (CAD$)
1	Bamboo	[602,737]	[2.00, 2.45]	[1.7,2.55]	[3.4,6.25]
2	Wrought Magnesium Alloys	[1.5e3,1.95e3]	[5.0, 6.49]	[2.5,2.8]	[12.5, 18.2]
3	Low Alloy Steel	7.80e3	25.95	[0.957, 1.15]	[24.83, 29.84]
4	CFRP, epoxy matrix (isotropic)	[1.5e3,1.6e3]	[5.0, 5.3]	[48.4,53. 8]	[242,285]
5	Titanium Alloys	[4.43e3,4.79e3]	[14.74,15.93]	[32.3, 35.3]	[476.1,562.3]

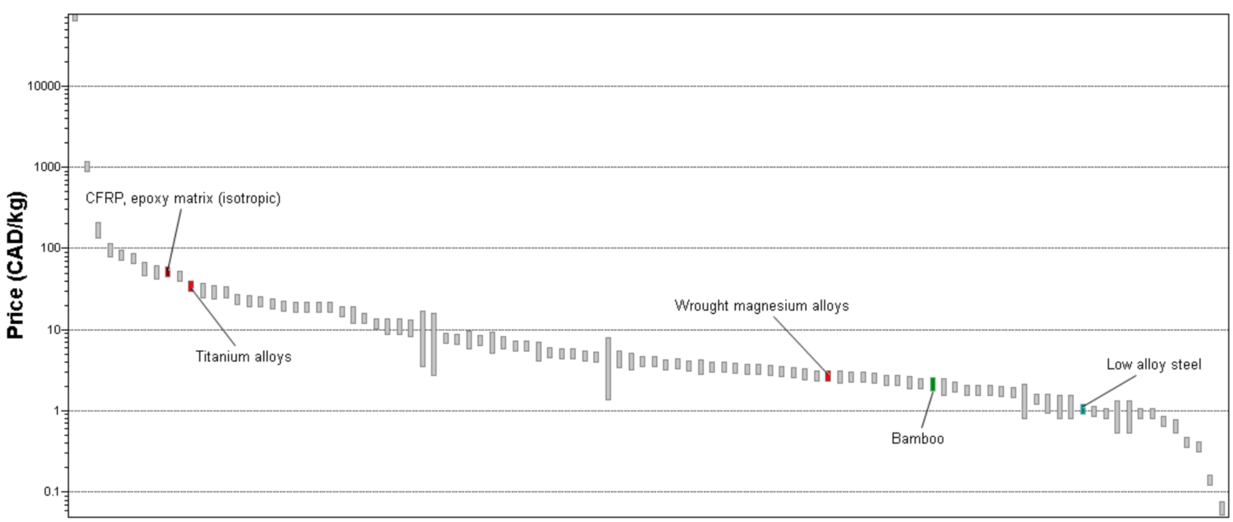


Figure 8: A Graph representing the price (CAD$) per (kg) of material.

The cost of the material isn't the only price tag we have to consider. In order to fabricate the turbine blade, we need to consider the cost in machinery, labor and energy. We can simplify this criterion by finding the Surface Area of the blade and multiply it by 6000[CAD/m^2] to calculate the cost of fabrication.

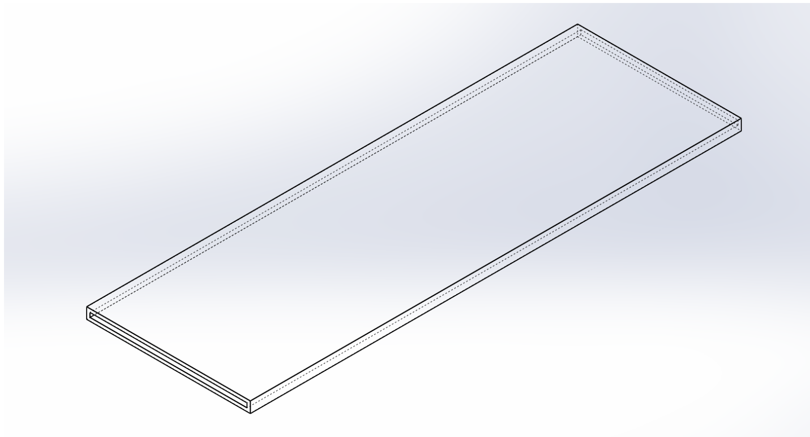


Figure 9: SolidWorks representation of Blade cavity

$$SA_{Slit} = (20 \cdot 300) - (288 \cdot 8) = 3690[mm^2]$$
$$SA_{Outter} = 2(900 \cdot 300) + 2(900 \cdot 20) + 2(3690) = 583380[mm^2]$$
$$SA_{Inner} = 2(900 \cdot 8) + 2(900 \cdot 288) = 532800[mm^2]$$

Therefore, the total surface area for the blade cavity is the sum of the Outer and Inner surface of the blade:

$$SA_{Total} = 1116180[mm^2] = 1.11618[m^2]$$
$$\text{Fabrication Cost (\$CAD)} = 1.11618[m^2] \cdot 6000[CAD/m^2\ ] = \$6697.08\ [CAD]$$

Comparing the fabrication costs to the material costs, the fabrication costs are much more significant than the material cost and therefore the relative costs between the materials once they are turned into blades, is minimal (less than 10% difference). Therefore, material selection does not have a significant impact on cost, and materials would preferably be selected based on other methods, as presented later on.

Eco Audit

Environmental impacts are a key factor of deciding which material to use, especially on an airplane part since the aviation industry has high environmental impacts, and a small percentage efficiency increase can translate to huge amounts of absolute energy or CO2 reductions.

An eco audit was performed in Grant EduPack to determine which material (of the best 3) is the best from an environmental standpoint. To determine this, the route from Beijing (the part's origin) to Vancouver was found. In total, there is 177km of truck-based land travel (40tonne 6 axel truck chosen based on China's truck regulations), and 10000km of ocean travel.

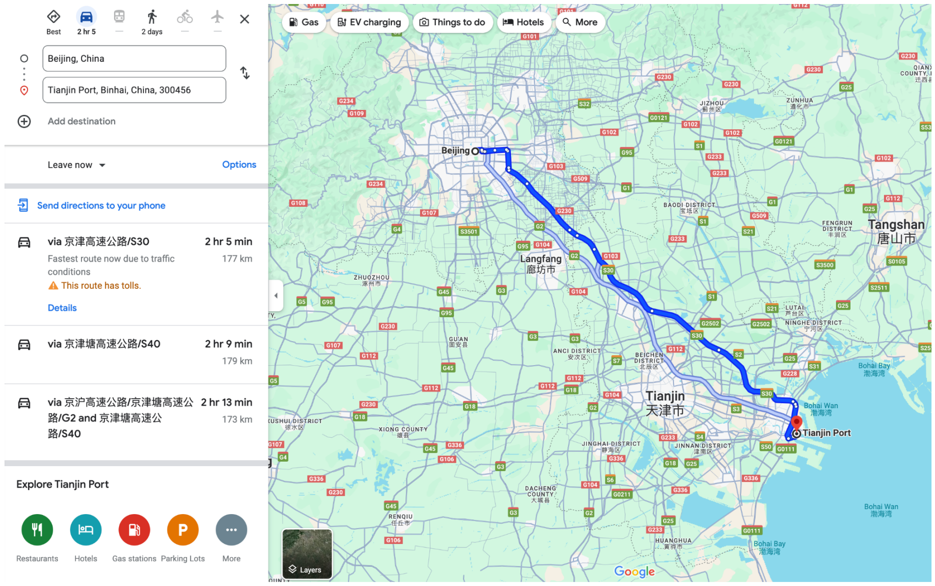


Figure 10: Route and distance from Beijing to Tianjin port

Beijing (origin of product) to Tianjin Port (closest large port) is about 177km. Shipping distance is aproximately 10000km.

In addition, further use case conditions were also assumed:

Number of blades	1000
End of life	Landfill
Product life	2 years
Usage	300 days/year
Traveled distance	10000 km/day

As well, the data was assumed for the 3 materials. The mass midpoint was chosen from the range of provided masses.

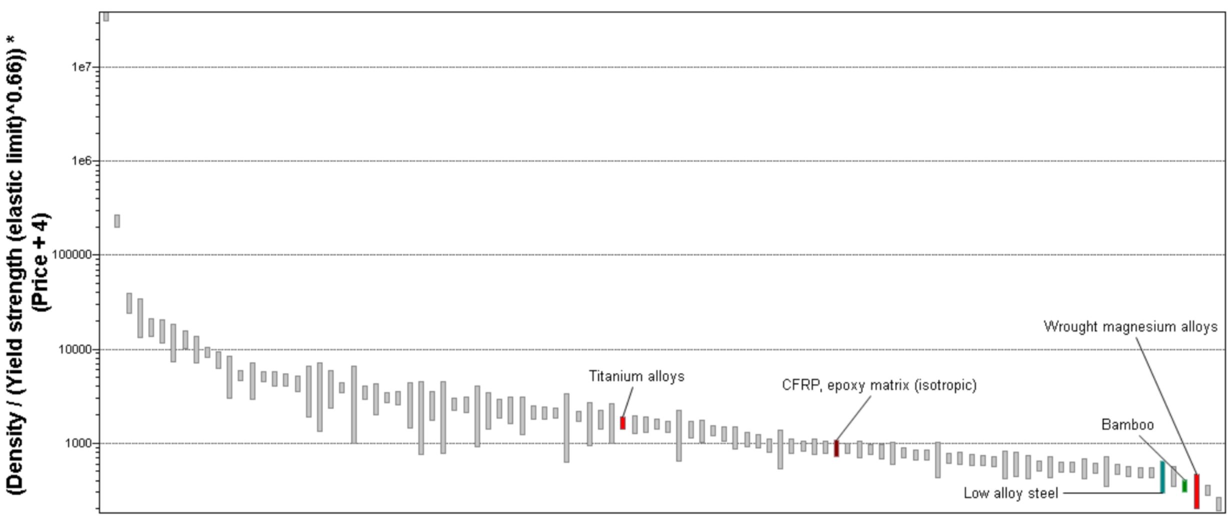
Material	Mass (Kg)	Process Type
Bamboo	2.22	N/A (negligible)
CFRP	5.15	Compression Molding
Wrought magnesium Alloys	5.75	Roll Forming

After running the Eco Audit, the results are as follows:

Material	Energy Consumption (J)	CO_2 Footprint (Kg)
Bamboo	8.67e13	6.24e6
CFRP	2.04e14	1.47e7
Magnesium	2.26e14	1.64e7

From this, Bamboo is clearly the most eco-friendly, with CFRP and Magnesium being second and third placed respectively. This is because the vast majority (>99%) of lifetime CO_2 emissions and energy usage are from the daily use of the parts; since they are on aircraft, the most important condition is mass since more mass requires more fuel to operate.

Penalty Function



$$Z = \left(\frac{Density}{Yield\ Strength^{0.66}}\right) \times (Price + 4)$$

The lower the Z, the better the tradeoff. Therefore, wrought magnesium alloy has the best trade off.

Summary of best overall material

When applying the constraints for the aircraft blade, there are 5 suitable types of materials:

- CFRP, epoxy matrix (isotropic)
- Bamboo
- Wrought magnesium Alloys.
- Titanium Alloys
- Low alloy steel

From these CFRP was selected as the best option. Justification for CFRP is below, as well as why the other materials were not selected

CFRP

CFRP has low weight, the highest strength to weight ratio, and a low environmental impact. Furthermore, it excels in all tests. It has the best vibrational fatigue by far and the best strength performance, and high fracture toughness. In addition, it is a tested fan material that has stood the test of time; the GE90, the engine on the 777, has been flown since 1990 and the fan blades are made of CFRP.

Bamboo

Bamboo is a lightweight, natural and strong material to be used for a turbine fan blade. However, there are a few properties that make it unsuitable for use in a turbofan. Firstly it is flammable, which is a huge safety concern on a jet engine. In addition it does not handle water well, and can decay or warm after prolonged use. Warping means that additional clearance is needed on the fan case, reducing efficiency. As well, the blade warping can lead to an unbalanced fan, which is extremely dangerous and can lead to the entire turbofan tearing itself apart. While on paper bamboo is a suitable material, in real world conditions, it is unviable.

Wrought magnesium Alloys

Magnesium is a lightweight and strong material to be used for a turbine fan blade. However, there are a few downsides that make CFRP the better option. It just barely meets the tensile strength requirements, and slightly higher weight than CFRP means it is worse for the environment and has higher operating costs.

Titanium Alloys

Titanium is a decent option, however CFRP surpasses it in almost all metrics. Titanium just barely meets the tensile strength requirements. In addition, its much higher weight (~3 times) means that it has a higher environmental impact and operating costs.

Low Alloy Steel

Low alloy steel is a heavy and cheap material and could work as a fan blade. However, there are much better options. It just barely meets the tensile strength requirements, and its high weight will lead to a high environmental impact and also higher cost to operate.

Conclusion

In conclusion, Carbon Fiber Reinforced Composites are the recommended choice. Further research could be conducted into the specific composition and manufacturing process of the CFRP. As well, it is recommended to experimentally test CFRP under rigorous environmental and real-world operating conditions, to ensure it passes all safety requirements.