Material Selection Process for Tow-Bar System

ME 8610 Semester Project

Team:

The Explorers!

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TABLE OF CONTENTS

Introduction

In our research project, we will be working through the material selection process of the towbar system. The research has been done to work with the towbar system used for Aviation Ground Operations for different operations like - Pushback and Pull-over operations for various aircraft.

As we know that an aircraft is devoid of the reverse mechanism. Some Aircraft possess the 'reverse thrust' mechanism coupled with the 'power back' mechanism, making aircrafts technically capable of leading reverse maneuver. Still, due to the probability of jet-blast in the vicinity of the airport terminal building, that might lead to severe damage to the terminal building, that's why most of the airports require the plane to be pushed back from the terminal building to the runway strip using an ‘external power’. Utilizing 'power back' operation could even eventually lead the aircraft engine to suck-up the sand and debris close to the engine, leading to catastrophic engine failure.

To achieve the desired objective of getting aircrafts 'pushed back' from the terminal building to the runway is performed using the pushback operation, using 'external power.' The external power, in this case, is provided by a 'pushback' truck. A 'pushback truck' is connected to the aircraft using a dedicated towbar for different aircraft types, respectively. Wherein the towbar is connected to the lunette and pintle assembly of the nose landing gear.

The cost of pushback operation per flight depends on the entire pushback distance, i.e., distance from the terminal to the runway. The pushback operations cost 0.36% of the overall aviation ground operations cost incurred over a given flight. The cost component is variable and will be more likely to increase with the congestion pricing at different airports.

Design Baselines

In this section, the design baselines for our material selection analysis are specified to lead the research. This section begins by highlighting the base material to lead our material selection process. AISI 4130 is extensively utilized to make towbars, as suggested by different OEM handbooks. We have chosen this as our base material. It is also popularly known as 'Light Weight Steel.' Leading the material selection analysis to choose alternatives of AISI 4130.

The towbar system in-reference for our material selection analysis is - commercial passenger aircraft towing operations. Product baselines for further investigation are taken as - commercial passenger narrow-body aircraft (Airbus A321). In pushback operations, different towbars are used for various aircraft types, such as - Different towbar are used for 'Wide Body' and 'Narrow Body' Aircraft. Specifically, we will be focusing on the narrow-body aircraft towing dynamics for our further analysis.

The maximum take-off weight: 93,500 kg/103 Tons (approximately) for Airbus A321 is taken as one of the design load constraints to lead analysis further.

Design Regulations & Compliance

This section will enlist the involved design regulations laid by the FAA (Federal Aviation Administration) under FAR (Federal Aviation Regulations). FAA serves as the regulatory body, which has constituted Federal Aviation Regulations to lead safe aviation operations. FAA periodically revises its guidelines with new-scenarios and issues regularly advisories through its circulars. FAR consists of a basic set of rules and guidelines that serve as the standard operating procedures for all commercial carriers. Compliance with the FAR and FAA's latest advisory circulars (AC) is mandatory for all commercial airlines to stay in business.

Under the FAR AC-00-65 & Title - 14, it has laid out guidance for towbars and towbar less movement of aircraft. The speed restrictions for both clear and cluttered ramp conditions have been introduced to prevent untoward towing mishaps. Further, it is followed by the mentioning types of towing vehicles that could be used depending on the aircraft to be towed. Sections of AC 00-34 take us through the momentum's effect during the towing process with various weights and speed restrictions. Advisory also recommend for the safe length for the towing operations. It also highlights 'best practices' for aircraft ground staff during towing operations.

As per the advisory, the towbar's safe length for A321 is specified as 4400mm. Advisory also mentions the factory of safety for towing operations, which ranges from 1.5 - 1.95. The towbar for A321 has been advised to be used along with the rotating adaptor. The adaptor head is responsible for providing the actual connection between the pushback truck and aircraft. Adaptor head consists of pintle and lunette assembly. The connection between the towbar and the NLG (Nose Landing Gear) depends on the aircraft's installed interlocking mechanism.

Factors Involved in Design

This section enlists and lays out the factors and criteria needed to consider during the towbar system's design process. First, we will specifically talk about the load profile for the given design specimen. The load profile references have been taken from Experimental data of the tests conducted by US Army Material Technology Laboratory for their Report Tl-9260 referenced in the references section below. The report in reference has been in context for designing a towbar for M1A1 and M1A2 tanks, but the load profile's experimental data elements will remain the same for our problem.

The experimental data consists of static and dynamic analysis to cover the load profile elements for both static and dynamic scenarios. It has been observed that most of the load is axial load, as the loads are axis-symmetric due to pushback operations. The second prominent type of load is Bending load during the towing process due to the friction produced between the lunette and pintle. The component is also expected to withstand buckling load. Though the axial load profile consists of both tensile and compressive loads, compressive strength would benefit the overall design. The torsional load is minimalistic due to the endpoint connection with universal joints at the ends, allowing an adequate degree of freedom for the rotational motion.

In our analysis considerations, all the above three forces have been considered, and lateral swaying has been neglected due to low-speed operational conditions of pushback. Some amount of swaying is required for effective maneuvering over turns.

Problem Formulation

In the problem formulation part, the overall design problem has been formulated. We'll start with laying out the function, followed by the associated constraints, the problem's objective, and summing up by listing the free variables in our given problem.

Function:
Towbar system (for Aviation Ground Operations)

Constraints:

- **Geometric Criteria:**
  - Minimum Length and Maximum Length Specified as per FAR.
  - Lunette and Pintle Dimensions are fixed.

- **Strength Criteria (Priority Criteria):**
  - It must possess adequate strength to function under compressive load environment and withstand critical buckling load. Strength criteria is the priority criteria, holds the highest priority over other constraints.

- **Stiffness Criteria:**
  - It must have adequate stiffness to withstand any deformation during the transportation.

- **NVH Criteria:**
  - It should have ability to Damp axis-symmetric excitations/longitudinal excitations in the line of pushback operations.
  - It should operate in large frequency range zone to prevent vulnerability of resonance. Low noise frequency profile is usually less damped in air and leaves zero to no scope of alterations to be carried out. The large Frequency range zone leaves ample scope to lead alterations (if required) to avoid any structural resonance by altering stiffness or mass.

- **Fracture Toughness Criteria:**
  - It must possess adequate Fracture Toughness to resist flaw-propagation in the operational environment.

- **Corrosion Resistance**
  - It must be corrosion resistant.

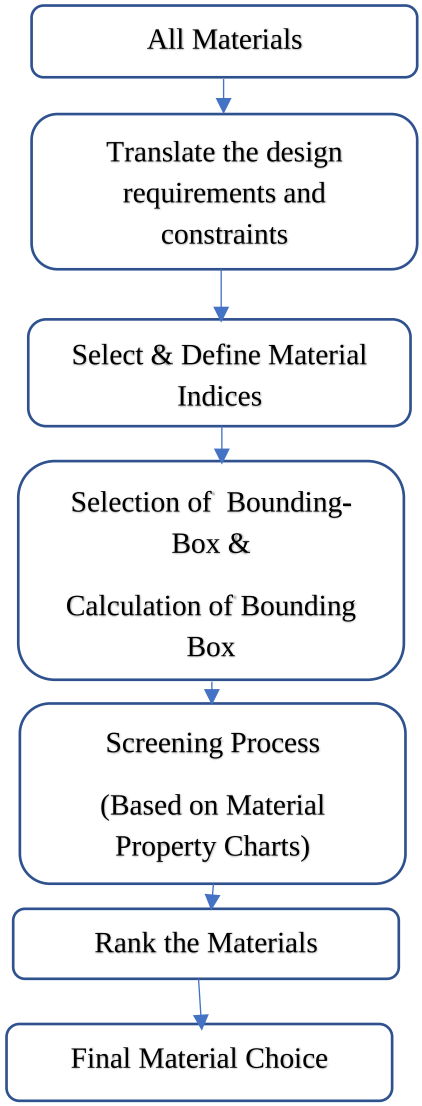
- **Objective:**
  - Minimize Mass
  - Minimize Cost

- **Free variables:**
  - Section Area
  - Choice of Material

Material Selection Process

In the above section, we will be working out the material selection process with laid out design constraints after formulating the problem. The design constraints will help us select suitable material indices as per the given problem. All the selected material indices should effectively address the involved design constraints.

In our analysis scheme, we will be modeling our towbar as a column to define relevant material indices.



Overview

We will start with a large sample-space of all the material pools with no-biasing or affinity towards a particular material in the material selection analysis. We will translate the laid design constraints and requirements to lead the screening process. Finally, ranking the materials based on the laid material indices to choose the final material from the entire materials pool.

Selection of Bounding Box

As mentioned in the design load profile and the design baselines above, the lunette eye assembly is fixed to NLG (Nose Landing Gear), and a suitable pintle needs to be adequately used to effectively provide the interlocking mechanism across the towbar and NLG connection end. The pintle mechanism is the driving force as to what cross-sectional area needs to be chosen.

The maximum possible cross-sectional area would serve as the upper bound, and the minimum possible cross-sectional area would serve as the lower bound of the bounding box. In the calculations, the load at take-off is taken as the base-design load multiplied with the FOS.

In the FOS selection, we chose the right extreme to address the worst load-case scenario, i.e., 1.95. The design load came out to be (approximately) 200 tons. Against the design load, the priority strength criteria were imposed. Successive four iterations between the upper bounds and the lower bounds were carried out. This helped us to define the bounding boxes for the Yield Strength. Bounding boxes enabled us further to narrow down our search in the material selection process.

Bounding Box Calculations

Design Load Profile: 200 Tons (FOS: 1.95)		
Tube Specimen	**Area of cross-section(m^2)**	**Yield Strength (MPa)**
T1	0.00190 $\mathbf{m^2}$	940 **MPa**
T2	0.00280 $\mathbf{m^2}$	636 **MPa**
T3	0.00320 $\mathbf{m^2}$	556 **MPa**
T4	0.00429 $\mathbf{m^2}$	414 **MPa**

Material Indices

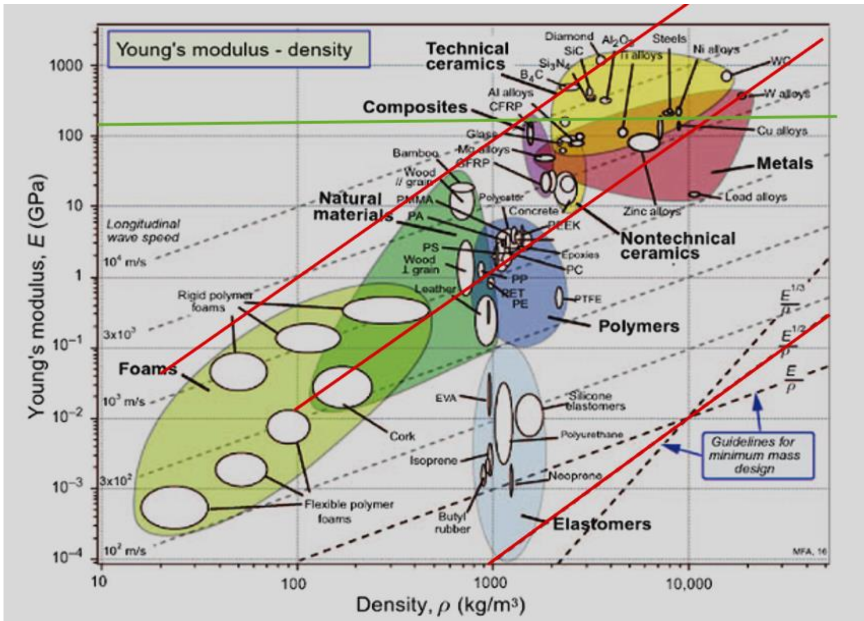
Case – I	**Stiffness Criteria:** Light & Stiff Column	$\frac{E^{1/2}}{\rho}$	Source: Ashby, Michael F.. (2011). Material Selection in Mechanical Design (4th Edition). Appendix – C1
Case – II	**Vibration Limited Design**	$\frac{E}{\rho}$	Source: Ashby, Michael F.. (2011). Material Selection in Mechanical Design (4th Edition). Appendix – C4
Case – III	**Fracture Toughness**	$\frac{K_{1C}}{\sigma}$	Source: Ashby, Michael F.. (2011). Material Selection in Mechanical Design (4th Edition). Appendix – C5
Case – IV	**Strength & Cost Criteria:** Light, Strong & Cheap	$\frac{\sigma}{\rho}$	Source: Ashby, Michael F.. (2011). Material Selection in Mechanical Design (4th Edition). Appendix – C2
Case – V	**Damping Character** Longitudinal Excitation Limiting	$\frac{\eta E}{\rho}$	A^3 Handbook

Selection Pedagogy

For the selection of the materials using the material indices chart, certain lines are created to make the selection process easier.

The blue lines were used to create the bounding box based on Strength criteria i.e. Yield strength. The red lines were used for the selection criteria and the green line represented the baseline material value i.e. AISI 4130.

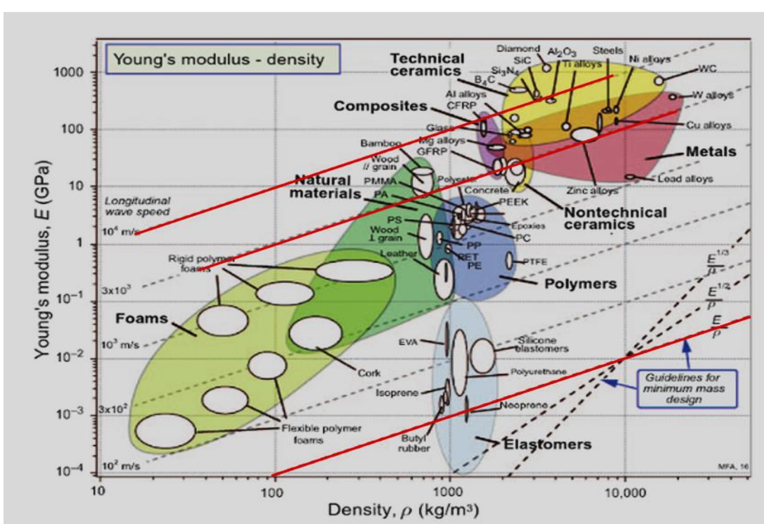
- Material Selection Charts
  1. **Case 1: Density vs Young's Modulus E(GPa)**



The above chart is used to undergo the primary screening of the materials on the basis of Stiffness Criteria ($E^{1/2}/\rho$). The red line in the chart is used for the selection process and the green line indicates the value of baseline material i.e. AISI 4130 in our case. In the first case, the broad screening of the materials is carried out, so that no material is left out in the selection process. Seven categories of materials have been selected in this case which are

a. Polymers
b. Foams
c. Non-Technical Ceramics
d. Technical Ceramics
e. Metals
f. Composites
g. Natural Materials

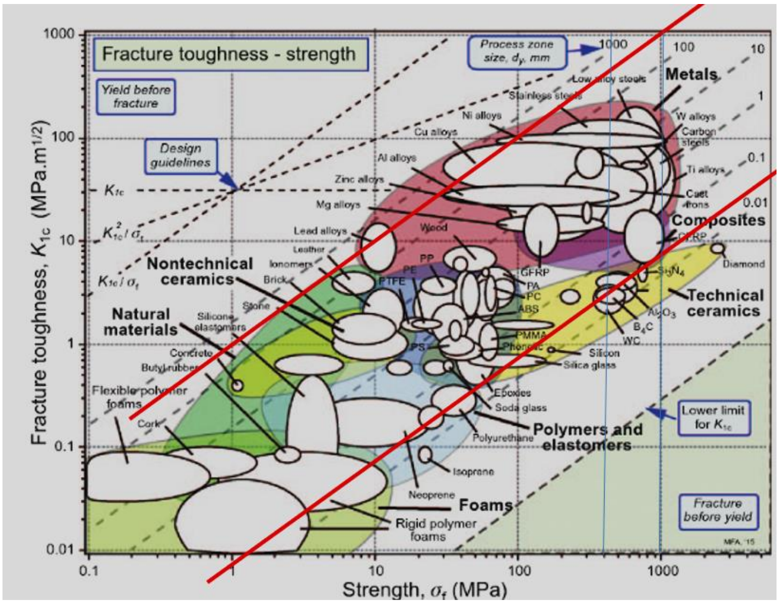
2. **Case 2: Density vs Young's Modulus E(GPa)**



The above chart is used to narrow down the selection process and the material families to meet the second criteria i.e. Vibration Limit Design. The red lines are used for the selection process and four categories of materials have been selected which are as follows:

a. Technical Ceramics
b. Composites
c. Metals
d. Natural Materials

3. Case 3: Fracture Toughness - Strength

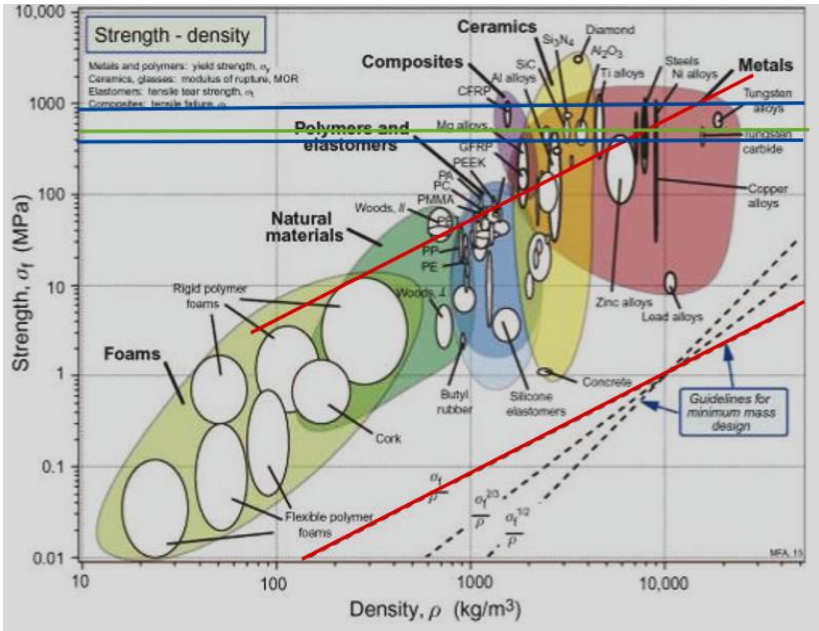


The 3rd Selection criteria i.e. Fracture Toughness is used to select the materials from the above 4 categories of materials. The range of yield strength (410MPa-940MPa) calculated initially is used to limit the strength of the materials and blue lines have been used to differentiate it in the above chart to create the Bounding box of yield strength. 1 composite, 4 Technical ceramics and 8 metals have been selected using the above chart and are listed below

Material Category	**Material**
Technical Ceramics	Si_3N_4
	Al_2O_3
	B_4C
	SiC
Composites	CFRP
Metals	Low Alloy Steel
	Carbon Steel
	Cast Iron
	Aluminum Alloy

	Titanium Alloy
	Tungsten Alloy
	Stainless Steel
	Nickel Alloy

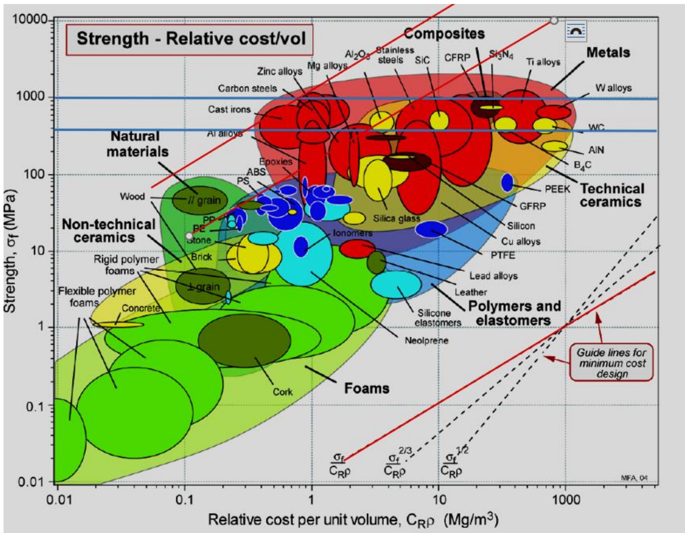
4. **Case 4a: Strength- Density chart**



The above chart is the Strength-Density chart and is used to meet the Strength Criteria. The Red line is used for selection process and has the equation (σ_f / ρ) and blue lines in it are used to create boundary box of yield strength to narrow down our selected materials. Now, we are left with the following materials

Material Category	**Material**
Technical Ceramics	Si_3N_4
	Al_2O_3
	SiC
Composites	CFRP
	Titanium Alloy
	Tungsten Alloy
	Stainless Steel
	Nickel Alloy

5. **Case 4b: Strength-Relative cost/volume**



The above chart is used to achieve the cost criteria along the strength criteria to further screen the materials and from the above chart to materials Al_2O_3 and Stainless Steel have been selected to attain strong and cheap material.

6. **Case 5: Damping Character**
   Final selection of the material is carried to meet the Damping Character criteria and the following table is used to obtain it.

Material	Loss coefficient	Density(ρ)	Young modulus (E)	M5	Final choice
Al_2O_3	3	3780 kg/m^3	$345*10^9$	$2.73*10^8$	**Al_2O_3**
Stainless steel	5	7480 kg/m^3	$203*10^9$	$1.35*10^8$	

Hence, using the parameters like Loss coefficient, Density, Young's modulus, and the values of 5th material index i.e. (η*E/ ρ), the final material that is selected is Aluminum oxide (Al_2O_3)

Conclusion & Rationality towards the Final Material

Finally, the material selected as per our analysis is Alumina/Aluminum Oxide (Al2O3). It happens to possess high mechanical strength, high compressive strength to withstand buckling loads. It possesses optimal bending resistance as per the subjected operational design loads. Alumina also has good NVH behavior, which would contribute towards limiting longitudinal excitations and prevent any low-frequency prone resonance profile. Above all, the product made from Alumina will be lightweight and thus, helping on the lines of 'Ease to Operate' for Aviation Ground Operations staff.

Coming to the point of fracture toughness, though the fracture toughness is less when compared to the stainless steel, the alumina oxide possesses an adequate amount of fracture toughness to prevent flaw-propagation in its given operational environment. Though Stainless Steel could be a good option with more fracture toughness, it would eventually increase the weight. Furthermore, for our material selection process, the strength to weight ratio is very integral. Its inability to prevent longitudinal excitations makes it the wrong choice for our application as shown in our fifth material index calculations.

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