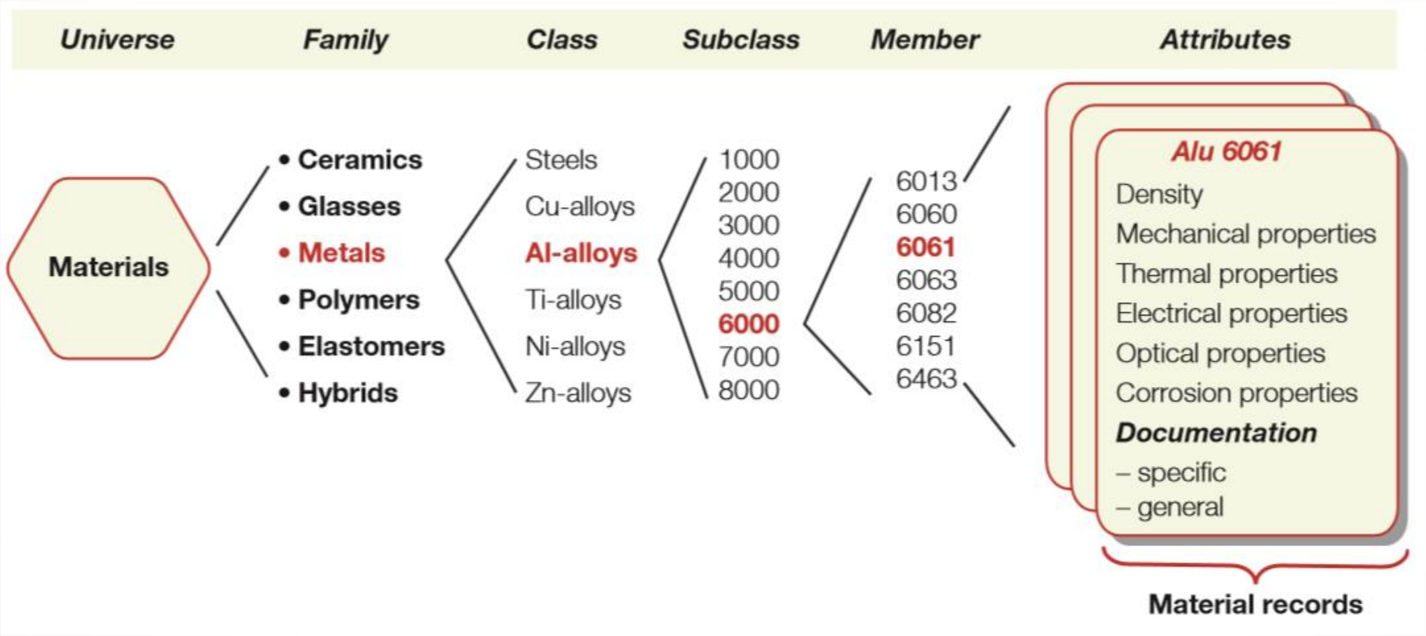
Materials Selection and Design

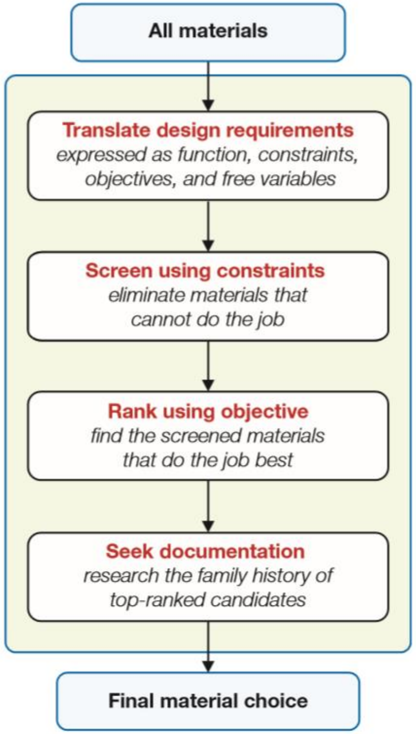
Materials Selection - Practice

- Each material is characterized by a set of attributes that include its mechanical, thermal, electrical, optical, and chemical properties; its processing characteristics; its cost and availability
- All these attributes make up the property profile
- Selection involves seeking the best match between the property profiles of the materials in the universe and the property profile required by the design



The basic procedure for material selection or establishing the link between material and function involves:

- Identifying the desired attribute profile
- Comparing this with those of real engineering materials to find the best match



It is important to start with the full menu of materials as options to avoid missing an innovative opportunity

If an innovative choice is to be made, it must be identified early in the design process

Too many decisions will have been taken and to many commitments will be made to allow radical change, if it is left to the end

The first step of the selection process is examining the design requirements to identify the constraints that they impose on material choice or **Translation**

- Any engineering component has one or more functions

e.g. to support a load, to contain a pressure, to transmit heat

- Constraints determine how functions are achieved

e.g. certain dimensions are fixed, components must carry the design loads or pressure without failure, component must insulate or conduct

- The design also has an objective

e.g. to make the component as cheap as possible, or as light, or as safe possible, or combination of those

- Certain parameters, free variables can be adjusted to optimize the objective

e.g. Dimensions that have not been constrained by design requirements can be varied

Function, constraints, objectives and free variables define the boundary conditions for selecting a material and also define the shape in the case of load bearing components

Table 5.1 Function, Constraints, Objectives, and Free Variables

Function	What does the component do?
Constraints*	What nonnegotiable conditions must be met? What negotiable but desirable conditions must be met?
Objective	What is to be maximized or minimized?
Free variable	Which parameters of the problem is the designer free to change?

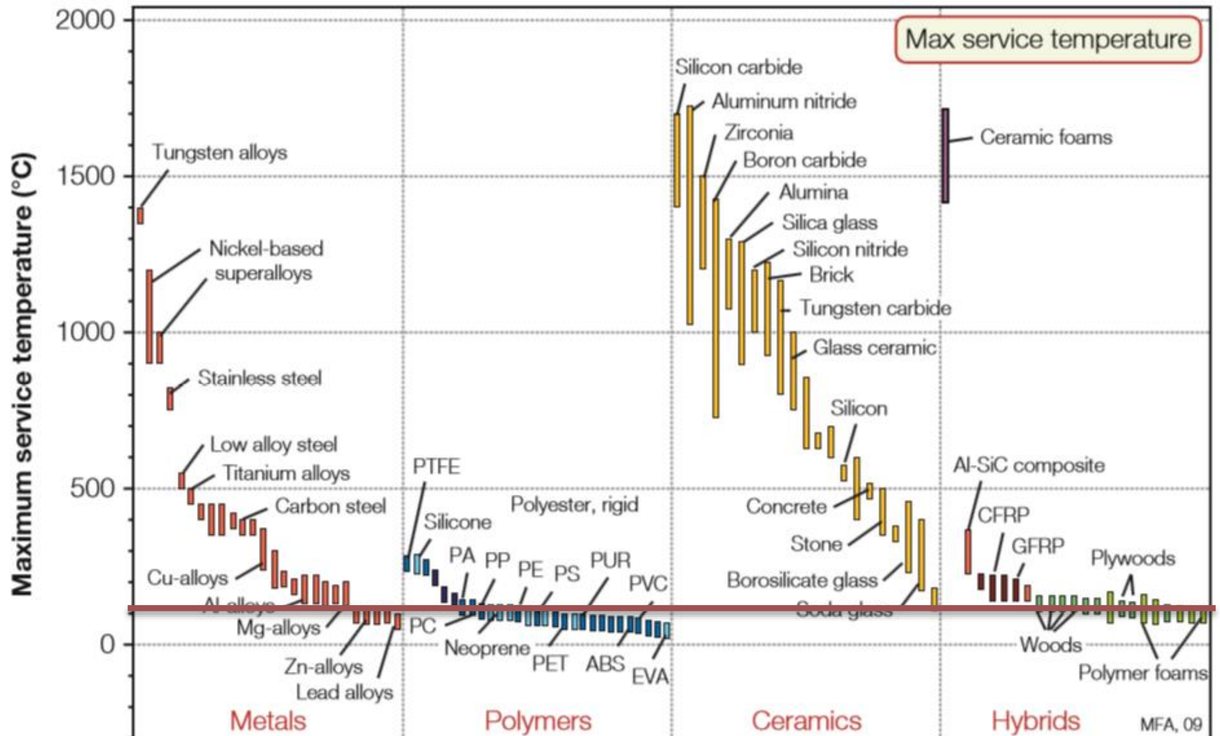
**It is sometimes useful to distinguish between "hard" and "soft" constraints. Stiffness and strength might be absolute requirements (hard constraints); cost might be negotiable (soft constraint).*

The wide material pool is narrowed by screening out the materials that cannot meet the requirements, or simply **Screening**

Materials with one or more of attributes that lie outside the limits set by the constraints are eliminated

e.g. the component must function in boiling water or the component must be transparent

These design requirements impose obvious limits on the attributes of maximum service temperature and optical transparency that successful material candidates must meet



Screened material pool is further narrowed by **ranking** the candidates by their ability to maximize performance

Optimization criteria need to be set for ordering the candidates that remain in the list

These are found in the material indices which measure how well a candidate that has passed the screening step can perform

When performance is limited by a single property, maximizing or minimizing a single property maximizes performance

It is more usual that performance is limited by a combination of properties

The property or property group that maximizes performance for a given design is called the material index

The outcome of the previous steps is a ranked short-list of candidates that meet the constraints and that maximize or minimize the ranking criterion

It is possible to just choose the top-ranked candidate, but it might have disadvantages

It is important to know its strengths and weaknesses, its reputation in design world

A detailed profile of each candidate or its **documentation** is sought at the last step

Documentation is descriptive, graphical, or pictorial

e.g. case studies of previous uses of the material, failure analyses and details of its corrosion, information about availability and pricing

Internet sources of information on all classes of materials

ASM Handbooks online, *www.asminternational.org/hbk/index.jsp*

ASM Alloy center, *www.asminternational.org/alloycenter/index.jsp*

ASM Materials Information, *www.asminternational.org/matinfo/index.jsp*

A to Z of Materials, *www.azom.com*

Design InSite, *www.designinsite.dk*

Goodfellow, *www.goodfellow.com*

K&K Associate's thermal connection, *www.tak2000.com*

Corrosion Source (databases), *www.corrosionsource.com*

Material Data Network, *www.matdata.net*

Materials (Research): Alfa Aesar, *www.alfa.com*

MatWeb, *www.matweb.com*

MSC datamart, *www.mscsoftware.com*

NASA Long Duration Exposure Facility, SETAS, *http://setas-www.larc.nasa.gov/LDEF/*

NPL MIDAS, *midas.npl.co.uk/midas/index.jsp*

Metals prices and economic reports

American Metal Market, *www.amm.com*

Business Communications Company, *www.bccresearch.com*

Daily Economic Indicators, *www.bullion.org.za*

Iron and Steel Statistics Bureau, *www.issb.co.uk*

Kitco Inc Gold & Precious Metal Prices, *www.kitco.com/market*

London Metal Exchange, *www.lme.co.uk*

Metal Bulletin, *www.metalbulletin.plc.uk*

Metal Powder Report, *www.metal-powder.net*

Metallurgia, *www.metallurgia-italiana.net*

Minerals Information, *http://minerals.usgs.gov/minerals*

Roskill Reports *www.roskill.com*

The Precious Metal and Gem Connection, *www.thebulliondesk.com*

Material indices

The performance of a component that perform a physical function or structural element is determined by three factors: the functional requirements, the geometry, and the properties of the material of which it is made

The performance P of the element is described by an equation of the form:

$$P = \left[\begin{pmatrix} \textit{Functional} \\ \textit{requirements, F} \end{pmatrix}, \begin{pmatrix} \textit{Geometric} \\ \textit{parameters, G} \end{pmatrix}, \begin{pmatrix} \textit{Material} \\ \textit{properties, M} \end{pmatrix} \right]$$

$$P = f(F, G, M)$$

where P, the performance metric, describes some aspect of the performance of the component: its mass, volume, cost, or life

Optimum design is the selection of the material and geometry that maximize or minimize P, according to its desirability

The three groups of parameters are separable when the equation can be written as

$$P = f_1(F) \cdot f_2(G) \cdot f_3(M)$$

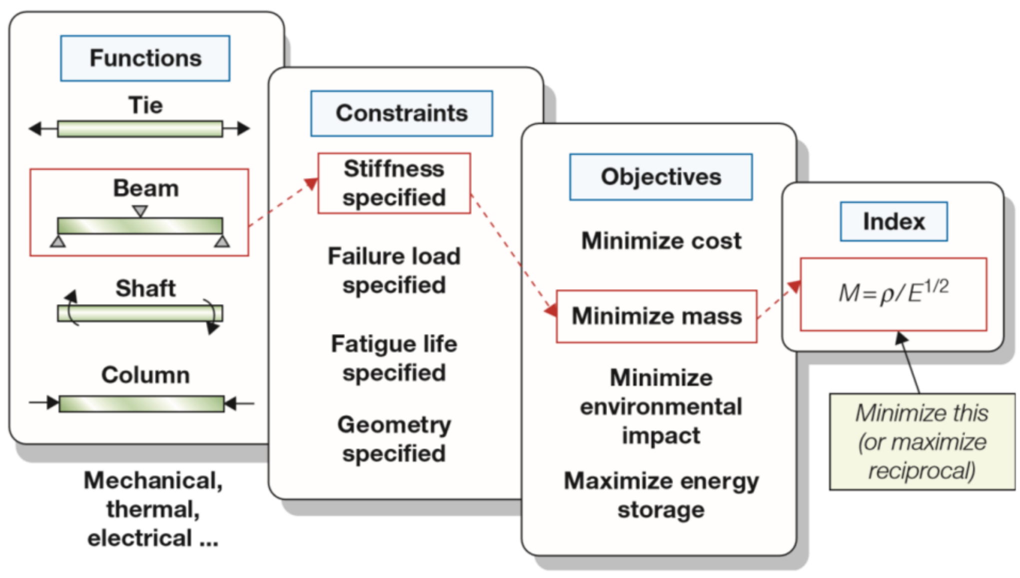
$$P = f_1(F) \cdot f_2(G) \cdot f_3(M)$$

When f_1, f_2, and f_3 are separate functions, the optimum choice of material becomes independent of the details of the design; it is the same for all geometries, G, and for all values of the function requirement, F

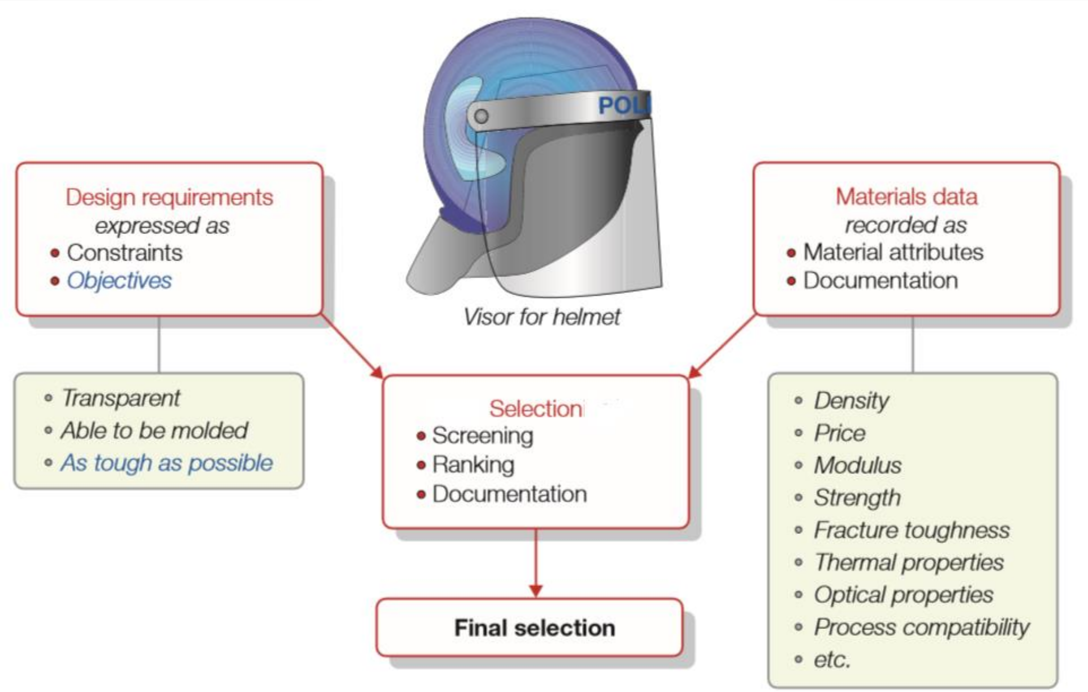
In this case the performance for all F and G is maximized by maximizing $f_3(M)$, which is called the material efficiency coefficient, or material index

Each combination of function, objective, and constraint leads to a material index

Material index is characteristic of the combination and thus of the function the component performs



Example – Material selection for the visor design for helmet



- Apply the constraints on the left to the materials on the right
- Screen out materials that fail to meet them and deliver a list of viable candidates
- Rank the list by the fracture toughness
- Explore in depth the three or so materials that meet the constraints and have the highest fracture toughness by seeking documentation for them

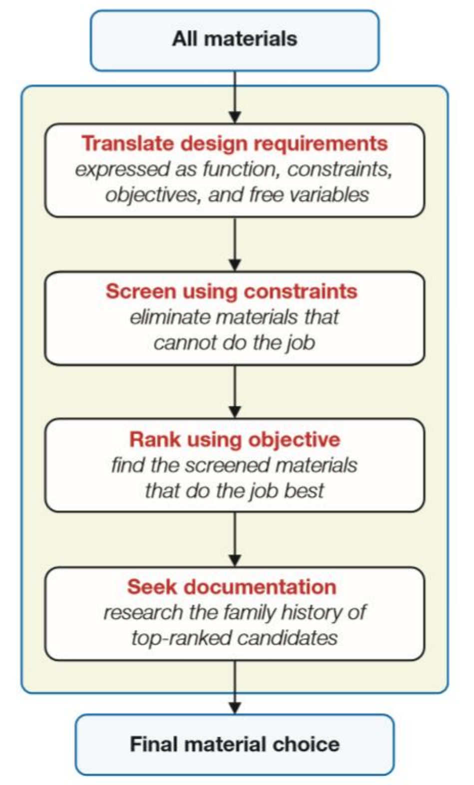
Example – Material selection for the visor design for helmet

Design requirements for the helmet visor

A material is required for the visor of a safety helmet to provide maximum facial protection.

Translation
To allow clear vision the visor must be optically transparent. To protect the face from the front, from the sides, and from below it must be doubly curved, requiring that the material can be molded. We thus have two constraints: transparency and ability to be molded.

Fracture of the visor would expose the face to damage; maximizing safety therefore translates into maximizing resistance to fracture. The material property that measures resistance to fracture is the fracture toughness, K_{1c}. The objective is therefore to maximize K_{1c}.



Screening and ranking for the helmet visor

A search for transparent materials that can be molded delivers the following list. The first four are thermoplastics; the last two, glasses. Fracture toughness values can be found in Appendix A.

Material	Average Fracture Toughness K_{1c} MPa.m$^{1/2}$
Polycarbonate (PC)	3.4
Cellulose acetate (CA)	1.7
Polymethyl methacrylate (acrylic, PMMA)	1.2
Polystyrene (PS)	0.9
Soda-lime glass	0.6
Borosilicate glass	0.6

The constraints have reduced the number of viable materials to six candidates. When ranked by fracture toughness, the top-ranked candidates are PC, CA, and PMMA.

Documentation for materials for the helmet visor

At this point it helps to know how the three top-ranked candidates listed in the last examples box are used. A quick web search reveals the following.

Polycarbonate
Safety shields and goggles; lenses; light fittings; safety helmets; laminated sheet for bullet-proof glazing.

Cellulose Acetate
Spectacle frames; lenses; goggles; tool handles; covers for television screens; decorative trim, steering wheels for cars.

PMMA, Plexiglas
Lenses of all types; cockpit canopies and aircraft windows; containers; tool handles; safety spectacles; lighting, automotive taillights.

This is encouraging: All three materials have a history of use for goggles and protective screening. The one that ranked highest in our list—polycarbonate—has a history of use for protective helmets. We select this material, confident that with its high fracture toughness it is the best choice.

Constraints set property limits, objective define material indices

The material index is a simple material property when the objective is not coupled to a constraint

The index becomes a group of properties when the two are coupled

Translation procedure for a design with objective coupled to constraints

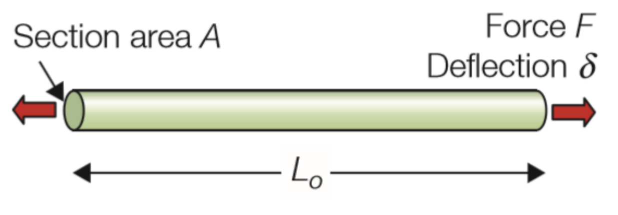
Table 5.6 Translation

Step No.	Action
1	Define the design requirements: *Function:* What does the component do? *Constraints:* Essential requirements that must be met: e.g., stiffness, strength, corrosion resistance, forming characteristics, etc. *Objective:* What is to be maximized or minimized? *Free variables:* Which are the unconstrained variables of the problem?
2	List the constraints (no yield, no fracture, no buckling, etc) and develop an equation for them if necessary.
3	Develop an equation for the objective in terms of the functional requirements, the geometry, and the material properties (*objective function*).
4	Identify the free (unspecified) variables.
5	Substitute the free variables from the constraint equations into the objective function.
6	Group the variables into three groups: functional requirements F, geometry G, and material properties M; thus Performance metric $P \le f_1(F) \cdot f_2(G) \cdot f_3(M)$ or performance metric $P \le f_1(F) \cdot f_2(G) \cdot f_3(M)$
7	Read off the material index, expressed as a quantity M that optimizes the performance metric P. M is the criterion of excellence.

Example - Material selection for the tie of a biplane

Table 5.2 Design Requirements for the Light, Strong Tie

Function	Tie rod
Constraints	Length L is specified (geometric constraint) Tie must support axial tensile load F^* without failing (functional constraint)
Objective	Minimize the mass m of the tie
Free variables	Cross-section area A Choice of material



Objective function: $m = A * l * \rho$

Specified variables: l, F

Free variables: A

Constraint equation: $\sigma_f \geq \frac{F^*}{A}$

Free variable equation: $A = \frac{F^*}{\sigma_f}$

Substitution of free variable into objective function: $m = A * l * \rho = \frac{F^*}{\sigma_f} * l * P$

Grouping the variables in terms of F, G, M: $m \geq \underbrace{(F^*)}_{\text{Functional constraint}}\underbrace{(L)}_{\text{Geometric constraint}}\underbrace{\left(\frac{\rho}{\sigma_f}\right)}_{\text{Material properties}}$

Material index to be maximized: $\boxed{\frac{\sigma_f}{\rho}}$

Ranking using design guidelines

For light and strong tie, the material index just derived is $\boxed{M = \frac{\sigma_f}{\rho}}$

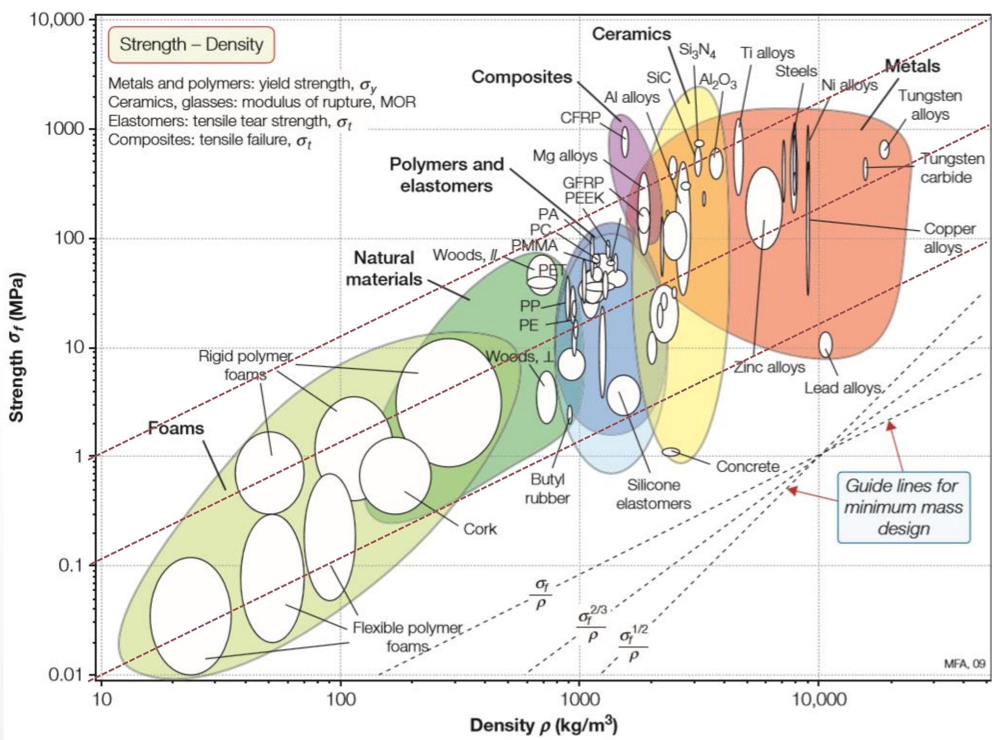
Design guidelines can be drawn on a strength vs density diagram by using this index

- Take logs: $\log \sigma_f = \log \rho + \log M$

  $y = mx + c$

  intercepts

- Design guidelines have slope 1 and intercept logM



Best materials for light, strong tie

Example - Material selection for the beam of a bipl

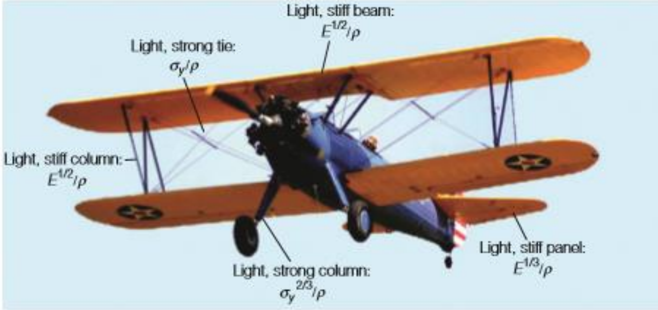
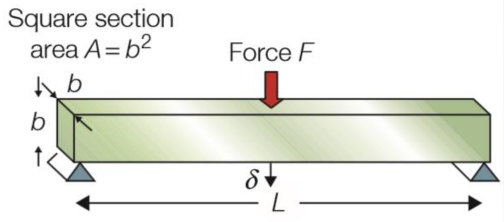


Table 5.4 Design Requirements for a Light, Stiff Beam

Function	Beam
Constraints	Length *L* is specified (geometric constraint) Section shape square (geometric constraint) Beam must support bending load *F* without deflecting too much, meaning that bending stiffness *S* is specified as *S** (functional constraint)
Objective	Minimize mass *m* of the beam
Free variables	Cross-section area *A* Choice of material



Objective function: $m = A * l * \rho$

Specified variables: l, F

Free variables: A

Constraint equation: $S = \frac{C_2 EI}{L^3} \geq S^*$ where C_2 is a constant

The second moment of area, I, for a square section beam is $\frac{b^4}{12} = \frac{A^2}{12}$

Free variable equation: $A = \left(\frac{12S^*L^3}{C_2 E}\right)^{1/2}$

Substitution of free variable into objective function: $m = A * l * \rho = \left(\frac{12S^*L^3}{C_2 E}\right)^{1/2} * l *$
P

Grouping the variables in terms of F, G, M:

$$m = \underbrace{\left(\frac{12S^*L^3}{C_2}\right)^{1/2}}_{\text{Functional constraint}} \underbrace{(L)}_{\text{Geometric constraints}} \underbrace{\left(\frac{\rho}{E^{1/2}}\right)}_{\text{Material properties}}$$

Material index to be maximized: $\boxed{\frac{E^{1/2}}{\rho}}$

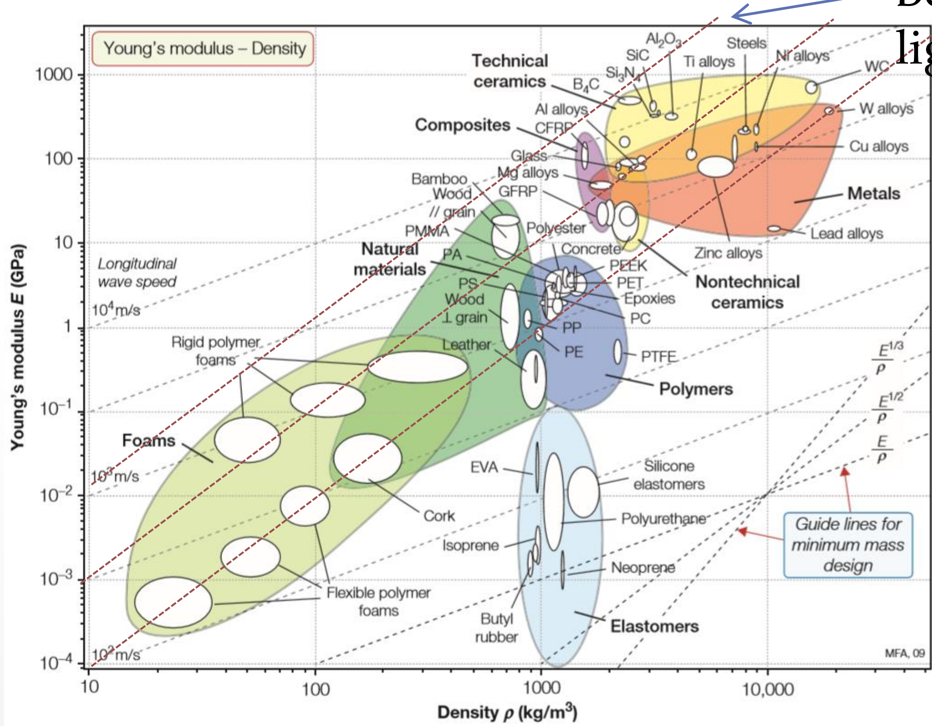
Ranking using design guidelines

For light and stiff beam, the material index just derived is $\boxed{M = \frac{E^{1/2}}{\rho}}$

Design guidelines can be drawn on a strength vs density diagram by using this index

- Take logs: $\log E = 2\log\rho + 2\log M$ intercepts
  $y = mx + c$
- Design guidelines have slope 2 and intercept 2logM

Best materials for light, stiff beam



Why Al-alloys are preferred for aircrafts rather than cheap steels?

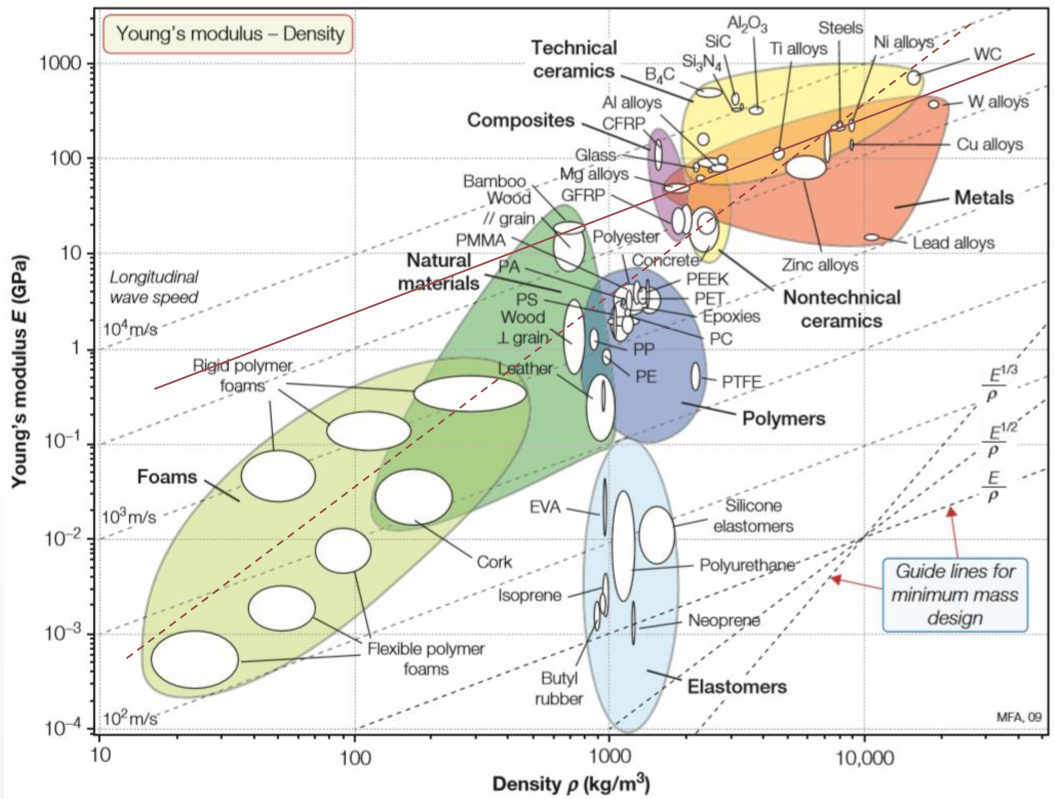
If the forces acting on aircrafts were purely tensile like a tie, the material index would be $M = \frac{E}{\rho}$

Design guideline for light, stiff tie (solid line) shows that both steel and alumina alloys would be good choices

However aircrafts experience bending loads especially on the wings

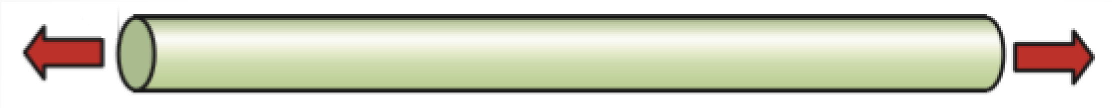
So the material index for a light and stiff beam applies to the aircrafts is $M = \frac{E^{1/2}}{\rho}$

According to the design guideline for light, stiff beams (dashed line), Al-alloys are better choice

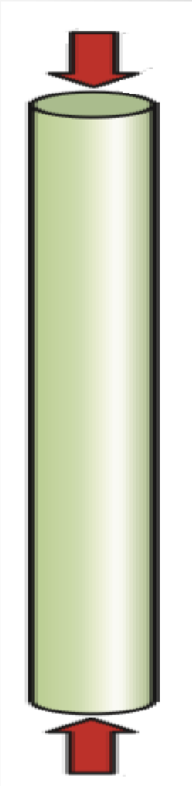


Four basic types of loading in engineering components

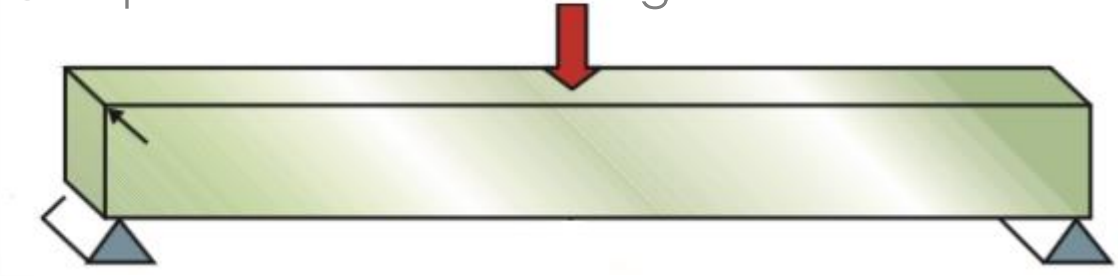
1. Ties: Components under axial tension



2. Columns: Components under axial compression



3. Beams: Components under bending moment



4. Shafts: Components under twisting moment

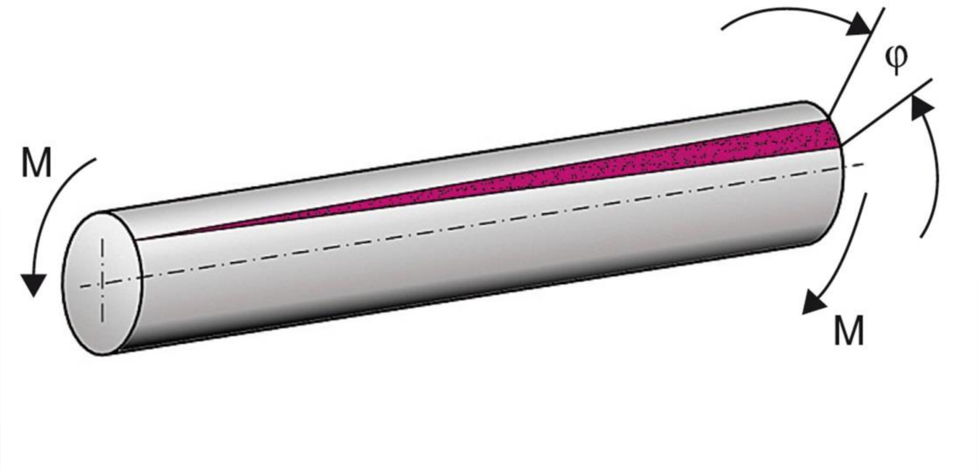


Table 5.5 Examples of Material Indices

Function, Objective, and Constraints	Index
Tie, minimum weight, stiffness prescribed	$\frac{E}{\rho}$
Beam, minimum weight, stiffness prescribed	$\frac{E^{1/2}}{\rho}$
Beam, minimum weight, strength prescribed	$\frac{\sigma_y^{2/3}}{\rho}$
Beam, minimum cost, stiffness prescribed	$\frac{E^{1/2}}{C_m\rho}$
Beam, minimum cost, strength prescribed	$\frac{\sigma_y^{2/3}}{C_m\rho}$
Column, minimum cost, buckling load prescribed	$\frac{E^{1/2}}{C_m\rho}$
Spring, minimum weight for given energy storage	$\frac{\sigma_y^2}{E\rho}$
Thermal insulation, minimum cost, heat flux prescribed	$\frac{1}{\lambda C_p\rho}$
Electromagnet, maximum field, temperature rise prescribed	$\frac{C_p\rho}{\rho_e}$

ρ = density; E = Young's modulus; σ_y = elastic limit; C_m = cost/kg; λ = thermal conductivity; ρ_e = electrical resistivity; C_p = specific heat

Example

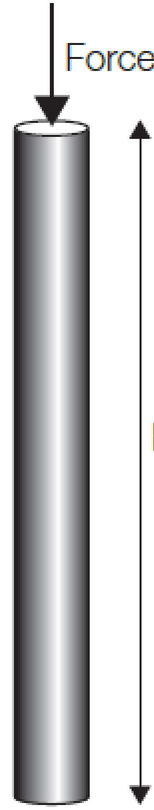


FIGURE E.15

E8.3 A cheap column that must not buckle or crush (Figure E.15) The best choice of material for a light, strong column depends on its aspect ratio: the ratio of its height H to its diameter D. This is because short, fat columns fail by crushing; tall, slender columns buckle instead.

Derive two performance equations for the material cost of a column of a solid circular section and of a specified height H, designed to support a load F (i.e., large compared to its self-load), one using the constraints that the column must not crush, the other that it must not buckle. The following table summarizes the needs.

Function	Column
Constraints	Must not fail by compressive crushing Must not buckle Height H and compressive load F specified
Objective	Minimize material cost C
Free variables	Diameter D Choice of material

Proceed as follows

1. Write down an expression for the material cost of the column—its mass times its cost per unit mass C_m.
2. Express the two constraints as equations, and use them to substitute for the free variable to find the cost of the column that will just support the load without failing by either mechanism.
3. Identify the material indices M_1 and M_2 that enter the two equations for the mass, showing that they are

$$M_1 = \left(\frac{C_m \rho}{\sigma_c}\right) \quad \text{and} \quad M_2 = \left[\frac{C_m \rho}{E^{1/2}}\right]$$

where C_m is the material cost per kg, ρ the material density, σ_c its crushing strength, and E its modulus.

Data for six possible candidates for the column are listed in the table that follows. Use these to identify candidate materials when $F = 10^5\ N$ and $H = 3\ m$. Ceramics are admissible here because they have high strength in compression.

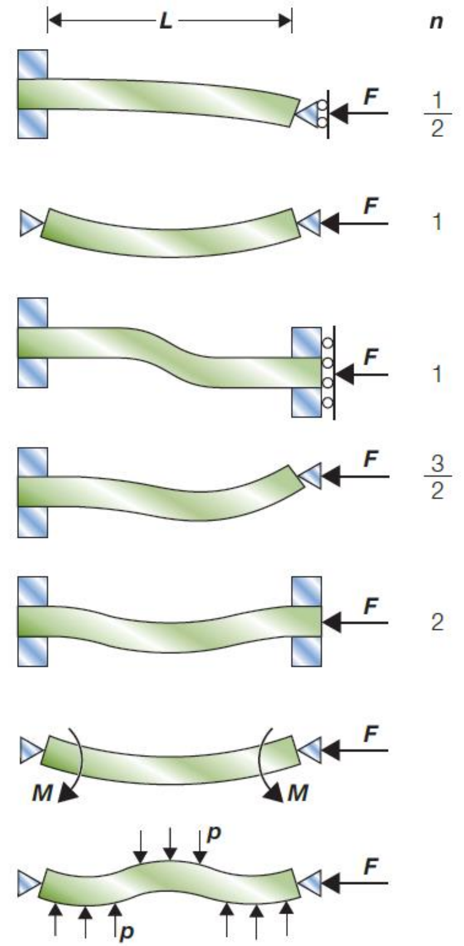
Data for Candidate Materials for the Column

Material	Density ρ (kg/m^3)	Cost/kg C_m (\$/kg)	Modulus E (MPa)	Compression Strength σ_c (MPa)
Wood (spruce)	700	0.5	10,000	25
Brick	2100	0.35	22,000	95
Granite	2600	0.6	20,000	150
Poured concrete	2300	0.08	20,000	13
Cast iron	7150	0.25	130,000	200
Structural steel	7850	0.4	210,000	300
Al alloy 6061	2700	1.2	69,000	150

Most not fail by compressive crushing or buckling under F=100000 N

Height is 3 m

- For a beam under simple tension the important characteristic of the section is its area, A. For other modes of loading, higher moments of the area are involved.
- The second moment, I, measures the resistance of the section to bending about a horizontal axis
- The moment, K, measures the resistance of the section to twisting
- The section modulus Z measures the surface stress generated by a given bending moment
- The moment Zp measures the resistance of the beam to fully plastic bending



$$F_{crit} = \frac{n^2 \pi^2 EI}{L}$$

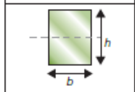
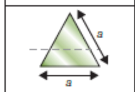
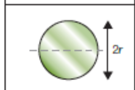
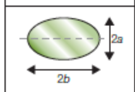
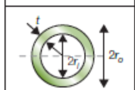
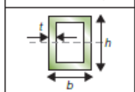
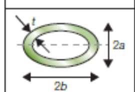
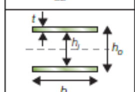
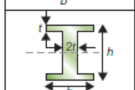
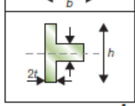
or

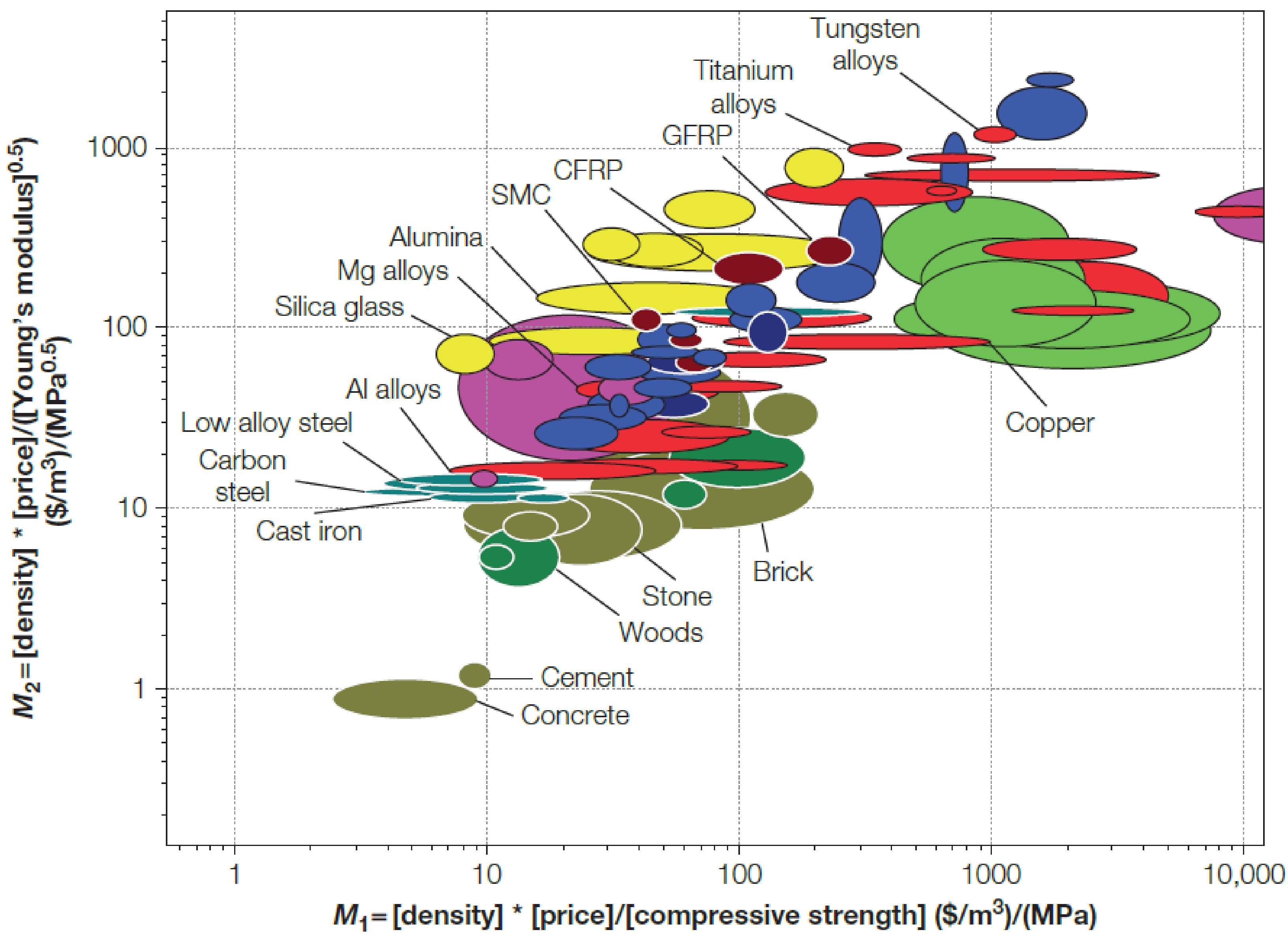
$$\frac{F_{crit}}{A} = \frac{n^2 \pi^2 E}{(L/r)^2}$$

F = Force (N)
M = Moment (Nm)
E = Young's modulus (N/m^3)
L = Length (m)
A = Section area (m^2)
I = See Table B.2 (m^4)
r = Gyration radius $(I/A)^{1/2}$ (m)
k = Foundation stiffness (N/m^2)
n = Half-wavelengths in buckled shape
p' = Pressure (N/m^2)

$$F_{crit} = \frac{\pi^2 EI}{L^2} - \frac{M^2}{4EI}$$

$$F_{crit} = \frac{n^2 \pi^2 EI}{L^2} - \frac{kL^2}{n^2}$$

Section Shape	Area A m^2	Moment I m^4	Moment K m^4	Moment Z m^3	Moment Z_p m^3
	bh	$\frac{bh^3}{12}$	$\frac{bh^3}{3}(1-0.58\frac{b}{h})$ $(h>b)$	$\frac{bh^2}{6}$	$\frac{bh^2}{4}$
	$\frac{\sqrt{3}}{4}a^2$	$\frac{a^4}{32\sqrt{3}}$	$\frac{\sqrt{3}a^4}{80}$	$\frac{a^3}{32}$	$\frac{3a^3}{64}$
	πr^2	$\frac{\pi}{4}r^4$	$\frac{\pi}{2}r^4$	$\frac{\pi}{4}r^3$	$\frac{\pi}{3}r^3$
	πab	$\frac{\pi}{4}a^3b$	$\frac{\pi a^3b^3}{(a^2+b^2)}$	$\frac{\pi}{4}a^2b$	$\frac{\pi}{3}a^2b$
	$\pi(r_o^2-r_i^2)$ $\approx 2\pi rt$	$\frac{\pi}{4}(r_o^4-r_i^4)$ $\approx \pi r^3t$	$\frac{\pi}{2}(r_o^4-r_i^4)$ $\approx 2\pi r^3t$	$\frac{\pi}{4r_o}(r_o^4-r_i^4)$ $\approx \pi r^2t$	$\frac{\pi}{3}(r_o^3-r_i^3)$ $\approx \pi r^2t$
	$2t(h+b)$ $(h, b>>t)$	$\frac{1}{6}h^3t(1+3\frac{b}{h})$	$\frac{2tb^2h^2}{(h+b)}(1-\frac{t}{h})^4$	$\frac{1}{3}h^2t(1+3\frac{b}{h})$	$bht(1+\frac{h}{2b})$
	$\pi(a+b)t$ $(a, b>>t)$	$\frac{\pi}{4}a^3t(1+\frac{3b}{a})$	$\frac{4\pi(ab)^{5/2}t}{(a^2+b^2)}$	$\frac{\pi}{4}a^2t(1+\frac{3b}{a})$	$\pi abt(2+\frac{a}{b})$
	$b(h_o-h_i)$ $\approx 2bt$ $(h, b>>t)$	$\frac{b}{12}(h_o^3-h_i^3)$ $\approx \frac{1}{2}bth_o^2$	–	$\frac{b}{6h_o}(h_o^3-h_i^3)$ $\approx bth_o$	$\frac{b}{4}(h_o^2-h_i^2)$ $\approx bth_o$
	$2t(h+b)$ $(h, b>>t)$	$\frac{1}{6}h^3t(1+3\frac{b}{h})$	$\frac{2}{3}bt^3(1+4\frac{h}{b})$	$\frac{1}{3}h^2t(1+3\frac{b}{h})$	$bht(1+\frac{h}{2b})$
	$2t(h+b)$ $(h, b>>t)$	$\frac{t}{6}(h^3+4bt^2)$	$\frac{t^3}{3}(8b+h)$	$\frac{t}{3h}(h^3+4bt^2)$	$\frac{th^2}{2}\{1+\frac{2t(b-2t)}{h^2}\}$



Tungsten alloys
Titanium alloys
GFRP
CFRP
SMC
Alumina
Mg alloys
Silica glass
Al alloys
Low alloy steel
Carbon steel
Cast iron
Copper
Brick
Stone
Woods
Cement
Concrete
1000
100
10
1
1
10
100
1000
10,000
M_2=[density] * [price]/([Young's modulus]$^{0.5}$) (\$/m^3)/(MPa$^{0.5}$)
M_1= [density] * [price]/[compressive strength] (\$/m^3)/(MPa)

Decision making

It is difficult to rank and choose the best materials if there are many objectives and many constraints

It is considerably easy if there are one objective and one constraint

e.g. Light and stiff column, $M_1=E^{1/2}/\rho$

In the usual case there are one objective and many constraints

e.g. Light and stiff-strong-tough beam, $M_1=E^{1/2}/\rho$, $M_2=\sigma_f^{2/3}/\rho$, $M_3= K_{1c}^{2/3}/\rho$

There are some methods helping decision making

Method of Weight Factors:

1. Tabulate the values of indices ($M_1=E^{1/2}/\rho$, $M_2=\sigma_f^{2/3}/\rho$)
2. Scale each index by dividing by its largest value so the largest value is 1 ($M_i' =M_i/M_{imax}$)
3. Determine a weight-factor w_i for each index which expresses its importance
4. Calculate the weighted index W_i for each candidate material ($W_i= w_i M_i'$)
5. Sum up the values of all W_i for each candidate material ($W_{total}= \Sigma W_i$)

Example – Light and stiff-strong beam, $M_1=E^{1/2}/\rho$, $M_2=\sigma_f^{2/3}/\rho$

Materials	M_1	M_2	M_1'	M_2'	W_1	W_2	W_{total}
Steel 1020	1.8	6.0	0.58	0.35	**0.41**	**0.10**	**0.51**
Al-6061-T4	3.1	9.0	1.00	0.53	**0.70**	**0.16**	**0.86**
Ti-6Al-4V	2.4	17.1	0.77	1.00	**0.54**	**0.30**	**0.84**

The final choice between competing candidates will often depend on local conditions

e.g. the availability of local suppliers, in-house expertise or equipment

A systematic procedure cannot help in this case, the decision must be based on local knowledge