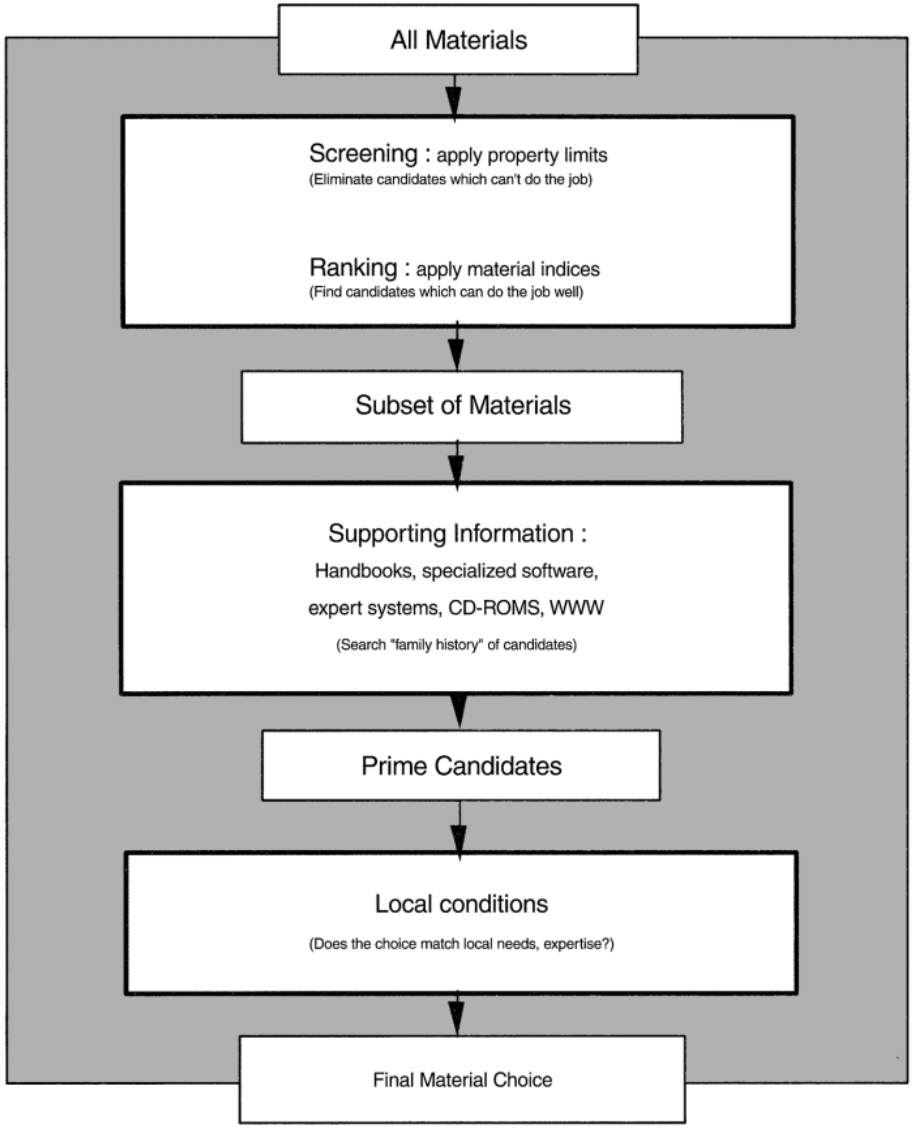
Selection of Engineering Materials

IM 515E

Dr Yehia M. Youssef

Material Selection Strategy



Screening and Ranking of Materials

- Unbiased selection requires that all materials are considered to be candidates until shown to be otherwise, using the steps detailed in the boxes of previous figure.
- The first of these, screening, eliminates candidates which cannot do the job at all because one or more of their attributes lies outside the limits imposed by the design.
- As examples, the requirement that ‘the component must function at 250°C, or that ‘the component must be transparent to light’ imposes obvious limits on the attributes of maximum service temperature and optical transparency which successful candidates must meet. We refer to these as **property limits**.

Engineering Materials & Their Properties

- Engineering Materials fall into **six** broad classes as shown in the figure:
  - Metals
  - Polymers
  - Elastomers
  - Ceramics
  - Glasses
  - Composites which are combinations of two or more of the above
- Members of each class have similar properties, similar processing routes and often they can be used for similar applications.

Screening and Ranking of Materials

- Property limits do not, however, help with ordering the candidates that remain. To do this we need optimization criteria.
- They are found in the material indices, developed below, which measure how well a candidate which has passed the limits can do the job.
- Familiar examples of indices are the specific stiffness E/ρ and the specific strength σ_f/ρ (E is the Young's modulus, σ_f is the failure strength and ρ is the density).
- The materials with the largest values of these indices are the best choice for a light, stiff tie-rod, or a light, strong tie-rod respectively.

Screening and Ranking of Materials

- There are many others, each associated with maximizing some aspect of performance.
- They allow ranking of materials by their ability to perform well in the given application.
- To summarize: property limits isolate candidates which are capable of doing the job; material indices identify those among them which can do the job well.

Deriving Property Limits and Material Indices

- How are the design requirements for a component (which define what it must do) translated into a prescription for a material?
- To answer this we must look at the function of the component, the constraints it must meet, and the objectives the designer has selected to optimize its performance.
- Any engineering component has one or more functions: to support a load, to contain a pressure, to transmit heat, and so forth.

Function, Objectives and Constraints

- In designing the component, the designer has an objective: to make it as cheap as possible, perhaps, or as light, or as safe, or perhaps some combination of these.
- This must be achieved subject to constraints: that certain dimensions are fixed, that the component must carry the given load or pressure without failure, that it can function in a certain range of temperature, and in a given environment, and many more.

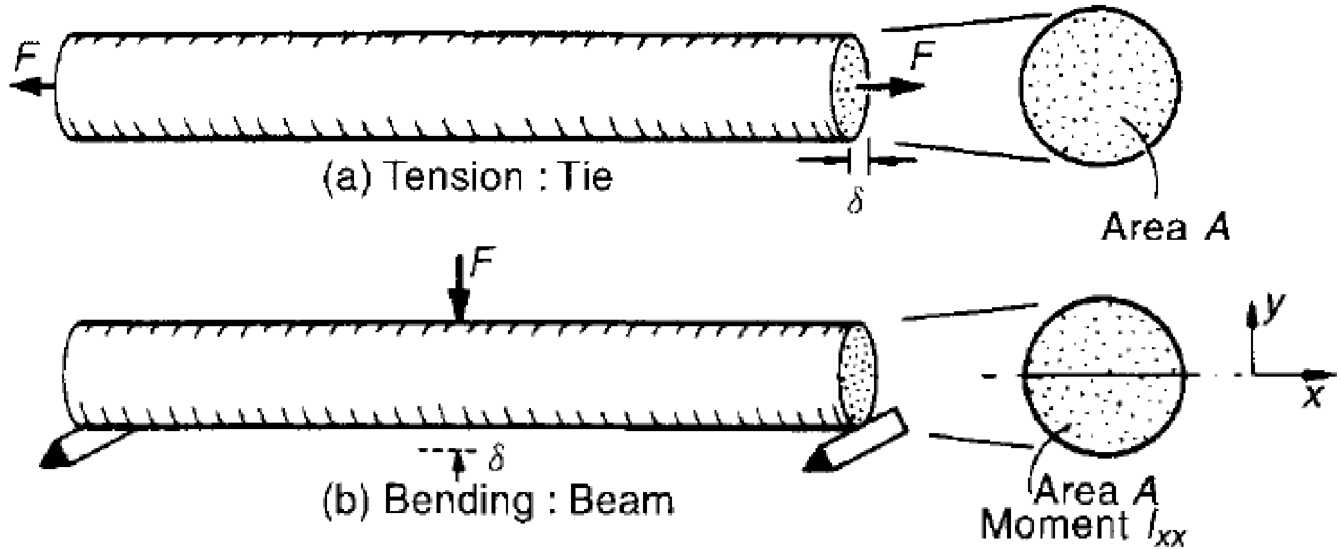
Function, Objectives and Constraints

- Function, objective and constraints (Table 5.1) define the boundary conditions for selecting a material and - in the case of load-bearing components – a shape for its cross-section.

Table 5.1 Function, objectives and constraints

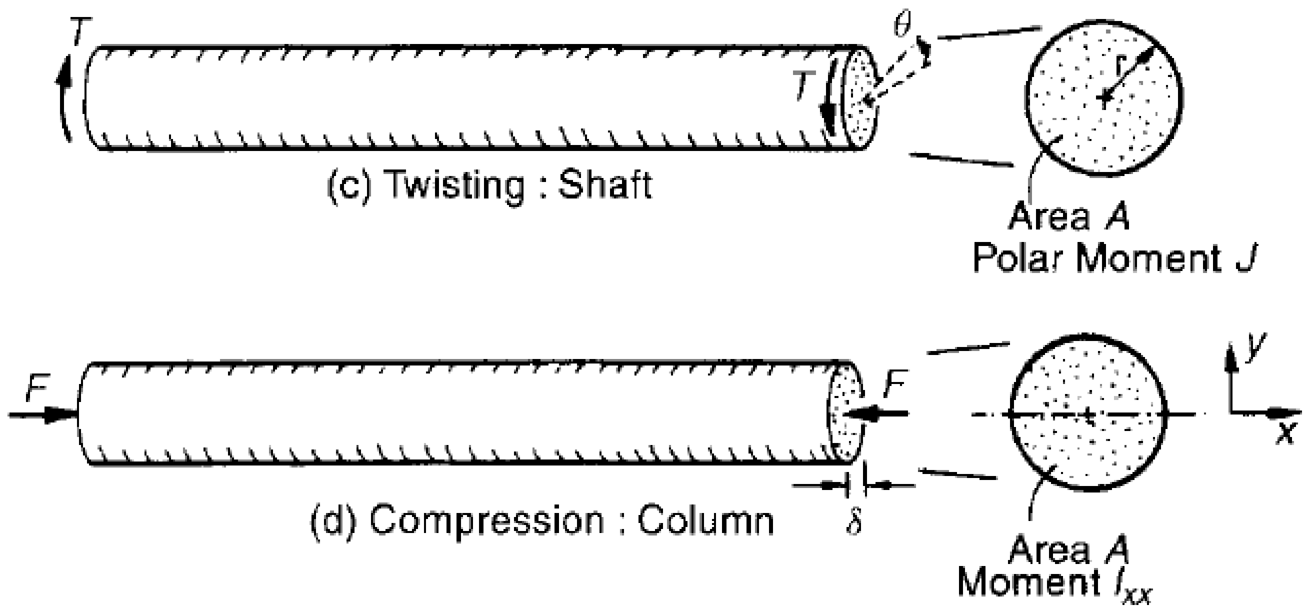
Function	What does component do?
Objective	What is to be maximized or minimized?
Constraints*	What non-negotiable conditions must be met? What negotiable but desirable conditions . . .?

A cylindrical tie-rod



A cylindrical tie-rod loaded (a) in tension, (b) in bending

A cylindrical tie-rod



A cylindrical tie-rod loaded (c) in torsion and (d) axially, as a column.

- The best choice of materials depends on the <u>mode of loading</u> and on the <u>design goal</u>; it is found by deriving the appropriate material index.

Property limits

- Some constraints translate directly into simple limits on material properties.
- If the component must operate at 250°C then all materials with a maximum service temperature less than this are eliminated.
- If it must be electrically insulating, then all material with a resistivity below 10^{20} $\mu\Omega$ cm are rejected.
- The screening step of the procedure of Figure 5.3 uses property limits derived in this way to reduce the kingdom of materials to an initial shortlist.
- Constraints on stiffness, strength and many other component characteristics are used in a different way.

Property limits

- This is because stiffness (to take as an example) can be achieved in more than one way: by choosing a material with a high modulus, certainly; but also by simply increasing the cross-section; or, in the case of bending-stiffness or stiffness in torsion, by giving the section an efficient shape.
- Achieving a specified stiffness (the constraint) involves a trade-off between these, and to resolve it we need to invoke an objective.
- The outcome of doing so is a material index. They are keys to optimized material selection. So how do you find them? box or I-section, or tube).

Material indices

- A material index is a combination of material properties which characterizes the performance of a material in a given application.
- First, a general statement of the scheme; then examples.
- Structural elements are components which perform a physical function: they carry loads, transmit heat, store energy and so on; in short, they satisfy functional requirements.
- The functional requirements are specified by the design: a tie must carry a specified tensile load; a spring must provide a given restoring force or store a given energy, a heat exchanger must transmit heat with a given heat flux, and so on.

Material indices

- The design of a structural element is specified by three things: the functional requirements, the geometry and the properties of the material of which it is made.
- The performance of the element is described by an equation of the form

$$p = f\left[\begin{pmatrix}\text{Functional}\\ \text{requirements,} \quad F\end{pmatrix}, \begin{pmatrix}\text{Geometric}\\ \text{parameters,} \quad G\end{pmatrix}, \begin{pmatrix}\text{Material}\\ \text{properties,} \quad M\end{pmatrix}\right] \tag{5.1}$$

or

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

where p describes some aspect of the performance of the component: its mass, or volume, or cost, or life for example; and ‘ f ’ means ‘a function of‘

Material indices

- Optimum design is the selection of the material and geometry which maximize or minimize p , according to its desirability or otherwise.
- The three groups of parameters in equation (5.1) are said to be separable when the equation can be written

$$p = f_1(F) \times f_2(G) \times f_3(M) \qquad (5.2)$$

where f_1, f_2 and f_3 are separate functions which are simply multiplied together.

- When the groups are separable, as they generally are, the optimum choice of material becomes independent of the details of the design; it is the same for all geometries, G, and for all the values of the functional requirement, F.

Material indices

- Then the optimum subset of materials can be identified without solving the complete design problem, or even knowing all the details of F and G.
- This enables enormous simplification: the performance for all F and G is maximized by maximizing $f_3(M)$, which is called the material efficiency coefficient, or material index for short.
- The remaining bit, $f_1(F).f_2(G)$, is related to the structural efficiency coefficient, or structural index.
- Each combination of function, objective and constraint leads to a material index; the index is characteristic of the combination.

Example 1: The material index for a light, strong, tie

- A design calls for a cylindrical tie-rod of specified length l, to carry a tensile force F without failure; it is to be of minimum mass.
- Here, ‘maximizing performance’ means ‘minimizing the mass while still carrying the load F safely’.
- Function, objective and constraints are listed in Table 5.2.

Table 5.2 Design requirements for the light tie

Function	Tie-rod
Objective	Minimize the mass
Constraints	(a) Length ℓ specified (b) Support tensile load F without failing

Example 1: The material index for a light, strong, tie

- We first seek an equation describing the quantity to be maximized or minimized.
- Here it is the mass m of the tie, and it is a minimum that we seek. This equation is called the objective function

$$m = A \times \ell \times \rho$$

  where A is the area of the cross-section and ρ is the density of the material of which it is made.
- The length ℓ and force F are specified and are therefore fixed; the cross-section A, is free.
- We can reduce the mass by reducing the cross-section, but there is a constraint: the section-area A must be sufficient to carry the tensile load F.

Example 1: The material index for a light, strong, tie

- This requires that:

$$\frac{F}{A} \leq \sigma_f \qquad (5.4)$$

where σ_f is the failure strength.

- Eliminating A between these two equations gives:

$$m \geq (F) \times (\ell) \times \left(\rho / \sigma_f \right) \qquad (5.5)$$

- The first bracket contains the specified load F. The second bracket contains the specified geometry (the length ℓ of the tie). The last bracket contains the material properties.
- The lightest tie which will carry F safely* is that made of the material with the smallest value of (ρ/σ_f).

Example 1: The material index for a light, strong, tie

- It is more natural to ask what must be maximized in order to maximize performance; we therefore invert the material properties in equation (5.5) and define the material index M as:

$$\boxed{M = \frac{\sigma_f}{\rho}}$$

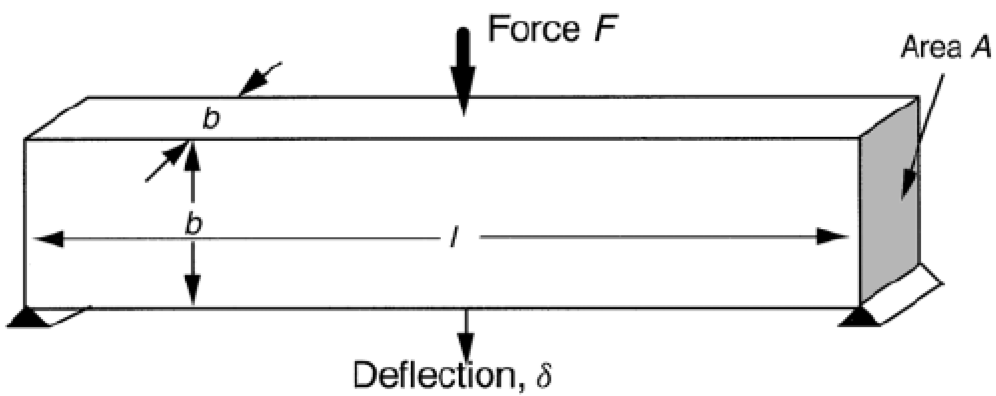
- The lightest tie-rod which will safely carry the load F without failing is that with the largest value of this index, the 'specific strength', mentioned earlier.
- A similar calculation for a light stiff tie leads to the index:

$$\boxed{M = \frac{E}{\rho}}$$

- where E is Young's modulus. This time the index is the 'specific stiffness'. But things are not always so simple.

Example 2: The material index for a light, stiff beam

- The mode of loading which most commonly dominates in engineering is not tension, but bending - think of floor joists, of wing spars, of golf-club shafts.
- Consider, then, a light beam of square section b x b and length ℓ loaded in bending which must meet a constraint on its stiffness S, meaning that it must not deflect more than δ under a load F (Figure 5.6).



Example 2: The material index for a light, stiff beam

- Table 5.3 itemizes the function, the objective and the constraints.

Table 5.3 Design requirements for the light stiff beam

Function	Beam
Objective	Minimize the mass
Constraints	(a) Length ℓ specified (b) Support bending load F without deflecting too much

- The constraint requires that S = F/δ be greater than this:

$$S = \frac{F}{\delta} \geq \frac{C_1 EI}{\ell^3}$$

where E is Young's modulus, C_1 is a constant which depends on the distribution of load and **I is the** second moment of the area of the section

Example 2: The material index for a light, stiff beam

- For a beam of square section ('Useful Solutions', Appendix A, Section A2), I is:

$$I = \frac{b^4}{12} = \frac{A^2}{12}$$

- The stiffness S and the length ℓ are specified; the section A is free.
- We can reduce the mass of the beam by reducing A, but only so far that the stiffness constraint is still met.
- Using these two equations to eliminate A in equation (5.3) gives:

$$m \geq \left(\frac{12S}{C_1 \ell}\right)^{1/2} \ell^3 \left(\frac{\rho}{E^{1/2}}\right)$$

- The brackets are ordered as before: functional requirement, geometry and material.

Example 2: The material index for a light, stiff beam

- The best materials for a light, stiff beam are those with large values of the material index:

$$\boxed{M = \frac{E^{1/2}}{\rho}}$$

- Here, as before, the properties have been inverted; to minimize the mass, we must maximize M.
- Note the procedure. The length of the rod or beam is specified but we are free to choose the section area A.
- The objective is to minimize its mass, m. We write an equation for m; it is called the objective function. But there is a constraint: the rod must carry the load F without yielding in tension (in the first example) or bending too much (in the second).

Example 2: The material index for a light, stiff beam

- Use this to eliminate the free variable A. Arrange the result in the format:

$$p = f_1(F) f_2(G) f_3(M)$$

  and read off the combination of properties, M, to be maximized.
- In deriving the index, we have assumed that the section of the beam remained square so that both edges changed in length when **A** changed. If one of the two dimensions is held fixed, the index changes.
- If only the height is free, it becomes:

$$\boxed{M = \frac{E^{1/3}}{\rho}}$$

- and if only the width is free, it becomes:

$$\boxed{M = \frac{E}{\rho}}$$

Derivation of Materials Index

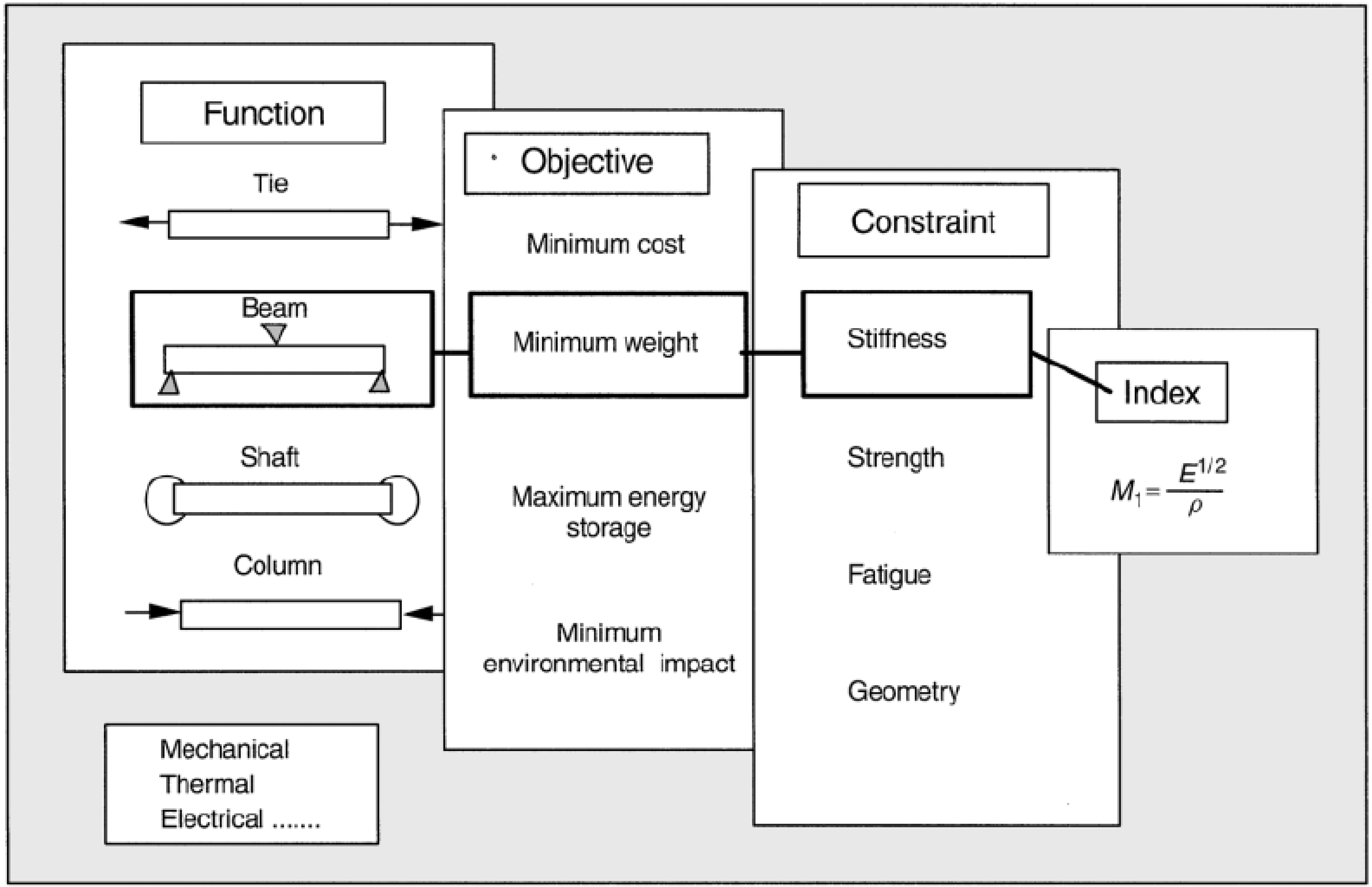


Fig. 5.5 The specification of function, objective and constraint leads to a materials index. The combination in the highlighted boxes leads to the index $E^{1/2}/\rho$.

Example 3: The material index for a cheap, stiff column

- Columns support compressive loads: the legs of a table; the pillars of the Parthenon. We seek materials for the cheapest cylindrical column of specified height, ℓ, which will safely support a load F (Figure 5.7). Table 5.5 lists the requirements.

Table 5.5 Design requirements for the cheap column

Function	Column
Objective	Minimize the cost
Constraints	(a) Length ℓ specified (b) Support compressive load F without buckling

Example 3: The material index for a cheap, stiff column

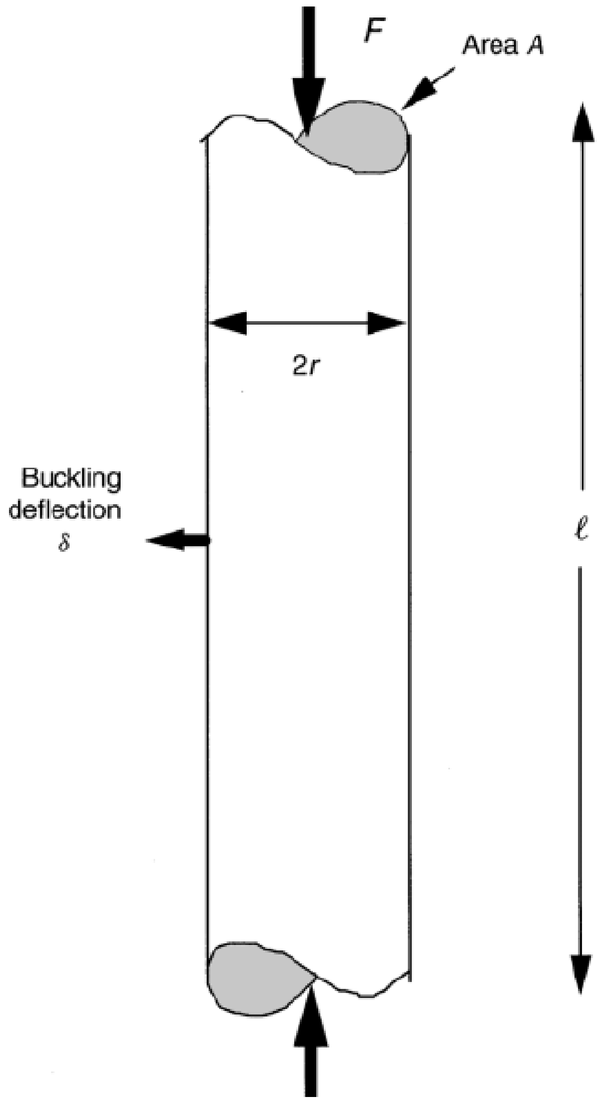


Fig.5.7 A column carrying a compressive load F. The constraint that it must not buckle determines the section area A.

Example 3: The material index for a cheap, stiff column

- A slender column uses less material than a fat one, and thus is cheaper; but it must not be so slender that it will buckle under the design load, F. The objective function is the cost:

$$C = A\ell C_m \rho$$

  where C_m, is the cost/kg of the material of the column. It will buckle elastically if F exceeds the Euler load, F_{crit}, found in Appendix A, 'Useful Solutions', Section A5. The design is safe if:

$$F \leq F_{\text{crit}} = \frac{n\pi^2 EI}{\ell^2}$$

  where n is a constant that depends on the end constraints and $I = \pi r^2/4 = A^2/4\pi$ is the second moment of area of the column (see Appendix A for both).

Example 3: The material index for a cheap, stiff column

- The load F and the length ℓ are specified; the free variable is the section-area A. Eliminating A between the last two equations, using the definition of **I** gives:

$$C \geq \left(\frac{4}{n\pi}\right)^{1/2} \left(\frac{F}{\ell^2}\right)^{1/2} \ell^3 \left(\frac{C_m \rho}{E^{1/2}}\right)$$

- The pattern is the usual one: functional requirement, geometry, material. The cost of the column is minimized by choosing materials with the largest value of the index:

$$\boxed{M = \frac{E^{1/2}}{C_m \rho}}$$

- From all this we refine the procedure for deriving a material index.