Department of Civil Engineering
IIT Madras

The Science, Engineering and Technology of Materials

An Introduction

Modern Construction Materials – Lecture 1
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Background

Basics

- Materials science involves the use of fundamental science in the understanding of the material and its behaviour.
- Materials engineering is the control of the properties for final useful applications. Should span the life of a material, from “cradle” to “grave”.
- Materials research solves problems and generates new technologies.

Roy, 1970

Background

Need for materials science training

- Knowledge of the science and fundamentals must precede the development of new and better materials.
- Provides better ability to the engineer and architect to judge the appropriateness of new and unconventional materials.

Background

Materials used in modern civil engineering

- Materials that have been used for centuries, such as wood (timber) and stone (rock).
- Materials used since the last century, like cement concrete and steel.
- New materials such as polymers and composites.

Background

Performance

- Materials developed more recently have superior properties and functions than those of the past.
- Performance requirements depend on the application.
- Cost often limits the targeted performance of the material.

Background

Why is construction materials technology important?

- Understanding of the behaviour of materials from a knowledge of their structure is essential.
- Information from material testing, processing, handling and fabrication, should be used along with basic science to give the foundation for materials technology needed for practice.

Background

Levels of information

- Molecular (nano- or micro-structure) level
- Material structure (or meso-scale) level
- Engineering (or macro-scale) level

Illston & Domone, 2001

Levels of Information

The molecular level

- Consideration of the material at the smallest scale, in terms of atoms, molecules and aggregations of molecules.
- Sizes of the particles are in the range of 10^{-7} to 10^{-3} mm.

  Examples: crystal structure of metals, calcium silicate hydrates in concrete, cellulose molecules in wood and many polymers used in composites.
- Physical structure and chemical composition can explain material properties and the evolution of the material with time.

  Examples: Relation between strength and porosity, and the durability of metal exposed to external substances.

Illston & Domone, 2001

Levels of Information

The material structure level

- Consideration of the material as a composite of different phases, which interact to give the total behaviour.
- Scale is in the range of 10^{-3} to 100 mm.

  ***Examples*:** a single brick, a wood cell and a piece of concrete.
- The material processing and multiphase response depends on:
  - Particle shape and size, distribution and concentration (dosage) of the phases
  - State and properties of the individual phases
  - Interfacial effects
- The phases and the interfaces can often be tested and their behaviour can be modeled.

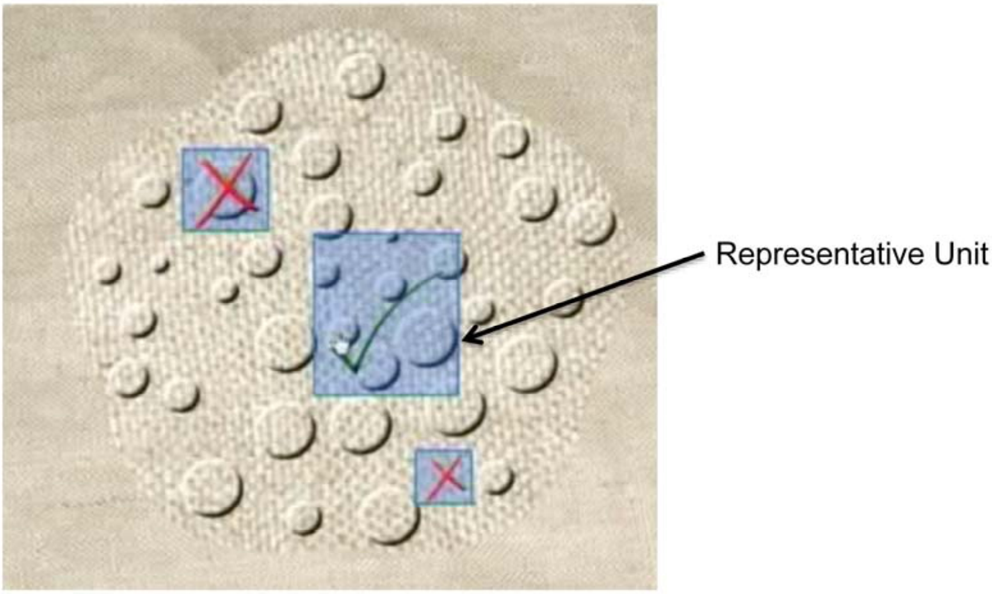
Illston & Domone, 2001

Levels of Information

The engineering level

- Consideration of the *total* material, normally taken to be homogenous and continuous.
- Scale is in the range of 10^{-3} to 1000 mm. The size of the representative unit is the minimum volume of the material that represents the entire system.
- The material can be tested to obtain its properties and behaviour. Models can be used to simulate its response within a larger structure.

Illston & Domone, 2001


Representative Unit

Selection of the Material

Considerations

- Cost-effectiveness for the purpose for which the structure is designed.
- The material should perform adequately during construction, in service, failure and demolition.
- Criteria that the material must satisfy:
  - Most often, strength, stiffness and durability.
  - Also, water-tightness, environment-friendliness, aesthetics and speed of construction.
  - Etc.

Illston & Domone, 2001

Selection of the Material

Material	Density [tonne/m^3]	Stiffness (E) [GPa]	Strength or Limiting Stress [MPa]*	Work to fracture (toughness) [kJ/m^2]	Relative cost per unit	
					mass	volume
Common pure metals	5-19	20-200	20-80	100-1000	-	-
Structural steel	7.85	195-205	235-450	100-130	1.0	1.0
High strength steel	7.85	205	260-1300	15-120	-	-
Cast iron	6.9-7.8	170-190	220-1000	0.2-0.3	-	-
Silica glass	2.6	94	50-200	0.01	3.4	1.1

* in tension unless stated; yield stress for metals, otherwise ultimate stress.

Illston & Domone, 2001

Selection of the Material

Material	Density [tonne/m^3]	Stiffness (E) [GPa]	Strength or Limiting Stress [MPa]*	Work to fracture (toughness) [kJ/m^2]	Relative cost per unit	
					mass	volume
Titanium and alloys	4.5	80-130	180-1320	25-115	27.5	1.6
Aluminium and alloys	2.7	69-79	40-630	8-30	5.0	1.7
Timber	0.17-0.98 (dry)	0.6-1.0 perp. grain 9-16 par. grain	90-200 (tens.) 15-90 (comp.)**	8-20 crack perp. grain 0.5-2 crack par. grain	-	-
Teak wood (parallel to grain)	0.63-0.72	6-15	95-155	0.3-0.4	1.5	0.09

* in tension unless stated; yield stress for metals, otherwise ultimate stress.
** on clear specimens.

Illston & Domone, 2001

Selection of the Material

Material	Density [tonne/m^3]	Stiffness (E) [GPa]	Strength or Limiting Stress [MPa]*	Work to fracture (toughness) [kJ/m^2]	Relative cost per unit	
					mass	volume
Concrete	1.8-2.5	20-45	4-10 (tens) 20-150 (comp)	0.03	0.7	0.12
Epoxy resin	1.1-1.4	2.6-3	30-100	0.1-0.3	3.8	0.53
Glass fibre composites	1.4-2.2	35-45	100-300	10-100	-	-
Carbon fibre composites	1.4-2.0	180-200	600-700	5-30	-	-
Nylon	1.1-1.2	2-4	50-90	2-4	7.5	1.1
Rubber	0.95-1.15	2-10	15-30	-	-	-

* in tension unless stated; yield stress for metals, otherwise ultimate stress.

Illston & Domone, 2001

Selection of the Material

Wide variety of properties

- The range of properties is very broad.
- Density varies by two orders of magnitude (wood to metals).
- Stiffness varies by two orders of magnitude (nylon to metals).
- Strength varies by three orders of magnitude (concrete to titanium).
- Work to fracture (fracture energy) varies by five orders of magnitude (glass to ductile metals). Very significant because it governs the flaw-resistance and the nature of failure. Difficult to compensate in structural design.

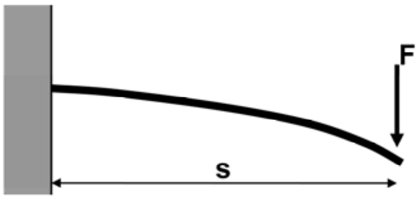
Illston & Domone, 2001

Selection of the Material: Variety of Properties

- In many cases, more than one material is fit for the purpose.
- For example, both steel and wood can carry tension; a wall can be of concrete, or stone, brick or block masonry.
- The choice of the material is made by considering the cost-effectiveness, often in conjunction with other considerations such as maximum weight, limiting dimensions and minimum useful life.

Selection of the Material

Simple example: Cantilever beam



Consider an application with a given load, span and beam width.

Free end deflection is given by: $u = \dfrac{Fs^3}{3EI}$

where E is the modulus of elasticity and I is the moment of inertia.

Selection of the Material: Beam example

For a beam of rectangular section,

$$I = \frac{bd^3}{12}$$

where *b* and *d* are the width and depth of the beam.

Using the two equations, the beam depth can be written as:

$$d = \left(4Fs^3/Ebu\right)^{1/3}$$

and, consequently, the weight of the beam as:

$$W = \rho sbd = \rho sb\left(4Fs^3/Ebu\right)^{1/3}$$

where ρ is the density.

Selection of the Material: Beam example

We now have:

$$W = s^2 b^{2/3} (4F/u)^{1/3} \left(\rho/E^{1/3}\right)$$

where all the terms except the last are fixed.

Therefore, *W* can only be minimised by maximising ($E^{1/3}/\rho$), which then becomes the selection criterion for obtaining the required stiffness at minimum weight.

Note: This is valid for any beam.

Illston & Domone, 2001

Selection of the Material: Beam example

Further, for the same example, we can derive the selection criterion for the strength of the beam.

For the cantilever, the maximum tensile stress is:

$$\sigma_{max} = 6Fs/bd^2$$

Therefore, the weight can be written as:

$$W = s^{3/2} b^{1/2} (6F)^{1/2} \left(\rho/\sigma_{limit}{}^{1/2}\right)$$

So, for desired strength at minimum weight, $(\sigma_{limit}{}^{1/2}/\rho)$ has to be maximised.

Selection of the Material: Beam example

If we need to minimise the cost (instead of weight),

the selection criteria for maximum stiffness and strength are $E^{1/3}/v_C$ and $\sigma_{max}^{1/2}/v_C$, respectively,

where v_C is the cost per unit volume = density × cost per unit weight (e.g., $v_C = \rho \times \$/\text{ton}$).

Illston & Domone, 2001

Selection of the Material: Beam example

The optimization terms for the four selection criteria derived earlier are given for different materials in the following tables.

Note that the weight and cost comparisons for the use of alternative materials for the cantilever have been made relative to structural steel (i.e., all terms for steel set as 1), with the material properties as in the table in the previous lecture.

Note that prices vary in time and by location, and have been used here only for illustration.

Selection of the Material: Beam example

Material	*Cost ($/ton)*	*Minimum weight*		*Minimum cost*	
		Stiffness criterion $E^{1/3}/\rho$	*Strength criterion* $\sigma_{max}{}^{1/2}/\rho$	*Stiffness criterion* $E^{1/3}/(\rho \times \$/ton)$	*Strength criterion* $\sigma_{max}{}^{1/2}/(\rho \times \$/ton)$
Structural steel	1.0	1.0	1.0	1.0	1.0
Silica glass	3.0	2.3	1.4	0.8	0.5
Titanium and alloys	30.0	1.5	2.6	0.05	0.1
Aluminium and alloys	5.0	2.1	3.4	0.4	0.7

Selection of the Material: Beam example

Material	Cost ($/ton)	Minimum weight		Minimum cost	
		Stiffness criterion $E^{1/3}/\rho$	Strength criterion $\sigma_{max}{}^{1/2}/\rho$	Stiffness criterion $E^{1/3}/(\rho \times \$/ton)$	Strength criterion $\sigma_{max}{}^{1/2}/(\rho \times \$/ton)$
Teak wood (par. to grain)	1.0	4.4	5.8	4.4	5.8
Concrete	0.5	1.7	0.9	3.5	1.8
Epoxy resin	4.0	1.4	2.0	0.3	0.5
Nylon	7.5	1.6	2.7	0.2	0.4

Selection of the Material: Beam example

When cost is neglected, titanium, aluminium, wood, glass and epoxy are the best.

However, when cost has to be minimised, conventional materials such as wood, concrete and steel score highest.

Many important aspects are neglected in this table, such as durability, toughness, construction time, transport, etc.

Illston & Domone, 2001

Selection of the Material

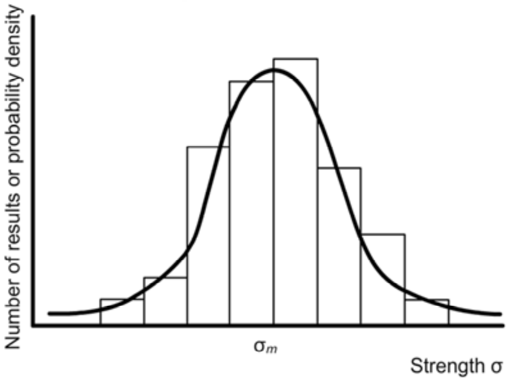
Variability of the Material Parameters

- The variability of the strength depends on the uniformity of the structure and composition of the material.
- This is of concern in engineering.
- The variability is taken into account in design through the characteristic strength.

Illston & Domone, 2001

Selection of the Material

Variability of the Material Parameters



for n results

$$\sigma_m = \sum \sigma / n$$

$$s^2 = \sum \left[(\sigma - \sigma_m)^2 / (n-1) \right]$$

$$c_v = s / \sigma_m$$

Typical bell-shaped (normal or Gaussian) distribution of strength within a series of samples of the same material:

$$y = \frac{1}{s\sqrt{2\pi}} \exp\left[-\frac{(\sigma - \sigma_m)^2}{2s^2} \right]$$

where y is the probability density, σ is the strength, σ_m is the mean, s is the standard deviation, and c_v is the coefficient of variation.

Selection of the Material

Variability of the Material Parameters

Typical values for mean strength and the variability in the material strength

Material	*Mean strength (MPa)*	*Coefficient of variation (%)*	*Comment*
Steel	460t	2	Structural mild steel
Concrete	40c	15	Typical concrete cube strength at 28 days

c = compression, t = tension

Illston & Domone, 2001

Selection of the Material: Variability

Material	*Mean strength (MPa)*	*Coefficient of variation (%)*	*Comment*
Timber	30t	35	Ungraded softwood
	120t	18	Knot free, straight grained softwood
	11t	10	Structural grade chipboard
Fibre cement composites	18t	10	Continuous polypropylene fibre with 6% volume fraction in stress direction
Masonry	20c	10	Small walls, brick on bed

c = compression, t = tension

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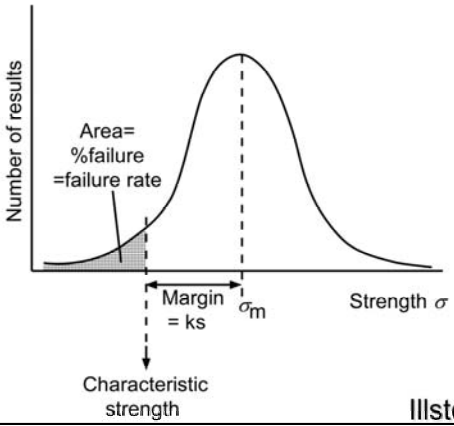
Selection of the Material: Variability

- Steel is manufactured through well-developed and controlled processes. Therefore, its variability is low.
- Wood is a natural material full of defects. Therefore, its variability is high. However, the variability in processed wood (plywood, agglomerated wood) is much lower.

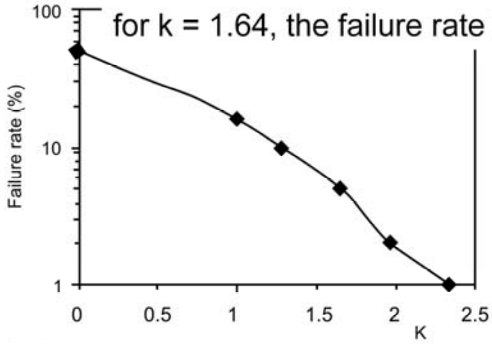
Selection of the Material: Variability

Variability of the Material Parameters

In design and material selection, a "safe" strength is normally used. This corresponds to a value at which the probability of failure is at an acceptable level. This safe strength is called the *characteristic* strength and given as $\sigma_{char} = \sigma_m - ks$.



for k = 0, the failure rate is 50%;
for k = 1.64, the failure rate is 5%.



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Selection of the Material: Summary

General considerations for construction materials

- Material properties (strength, stiffness)
- Cost
- Useful life
- Variability

References

- *Construction Materials: Their nature and behaviour*, Eds. J.M. Illston and P.L.J. Domone, Spon Press, 2001.
- *Materials Science and Engineering in the United States*, Ed. R. Roy, Pennsylvania State University, 1970.
- *The Science and Technology of Civil Engineering Materials*, J.F. Young, S. Mindess, R.J. Gray & A. Bentur, Prentice Hall, 1998