16.001 Unified Engineering
Materials and Structures

Instructor: Raúl Radovitzky
Teaching Assistants: Grégoire Chomette, Michelle Xu, and Daniel Pickard
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Transverse loading of slender structural elements: Beam Theory

Reading: CDL Chap. 3, 7 and 8

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Staff

Instructor:

Raúl Radovitzky
Research interests:

- Computational Mechanics of Materials and Structures
- Algorithms for extreme-scale computing
- Material deformation and failure response under extreme conditions
- Nanotechnology - Material systems for protection
- System reliability analysis: jet engines, rocket tanks
- Risk assessment: asteroid break-up, hypervelocity impact

Teaching Assistant:

Teaching Assistants Grégoire Chomette

Unified M&S, general considerations

Interaction in this class is key

- bring name cards
- ask questions
- you will be asked questions, be proactive, take risks (class is a controlled environment)
- **We are a learning community!!**

Advanced Readings are key: come prepared

Textbooks:

- Crandall, Dahl, Lardner: An Introduction to the Mechanics of Solids (CDL)
- Ashby & Jones: Introduction to Engineering Materials (AJ)
- Connor & Faraji: Fundamentals of Structural Engineering (Another great MIT book with a Civil Engineering focus) (Online Access)
- Hibbeler: Statics, Engineering Mechanics
- Advanced material: 16.20 notes

Introduction to Materials and Structures

Reading assignments: CDL 1.1, AJ Ch. 1

What is a Structure?

Definition

A structure refers to a body or system of connected parts designed and constructed to fulfill a specific function or functions:

- give shape
- support a load
- conduct power (electromagnetic, thermal)
- absorb or mitigate energy (vibrations, impact, EM radiation, heat)
- insulate, reflect, protect
- provide comfort

Structural Engineering

It is the discipline concerned with the analysis, design and optimization of load-bearing structures.

Broad steps in creating a structure

- identify loads structure will experience in its expected life
- determine suitable arrangement of structural elements
- select materials and dimensions
- define fabrication/assembly process
- monitor structure over operational life

Structural Design Requirements:

- satisfy design criteria: fulfill expected function
- maintain structural integrity throughout operation, guarantee safety
    - strength (bear peak loads in service)
    - stiffness (limit maximum deformation)
    - longevity (last long enough)
- optimize for fabrication and operational cost

Source: NASA/public domain

Structural integrity vs. Structural failure

Definition

Structural integrity refers to the fitness of a component or structure to perform its design function during the structure's operational life

Structural integrity ensures avoidance of catastrophic failure. Localized failure should not cause collapse of entire structure.

Definition

Structural failure refers to the loss of structural integrity, which is the loss of the load-carrying capacity of a component or member within a structure, or of the structure itself.

Examples of structural failures and tests

Aloha Airlines 243, 1988.

Simulation blade-off test

Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations.

Cost considerations: Weight vs. safety?

Saving a pound of weight means more:

- payload (extra passengers, more satellites, ...)
- fuel (range, duration)
- performance (more versatility, speed, generally military)

Amount industries (civilian) are willing to pay to save a pound of weight:

- Satellites \$10k - \$50k (w/o servicing)
- Transport Aircraft \$100 - \$200
- General Aircraft \$25 - \$50
- Automobile almost \$0

Cost to reach low-Earth orbit

2018, \$ per kg of cargo, principal launch vehicle

*United Launch Alliance, a partnership of Boeing and Lockheed Martin †Non-reusable version ‡France, Italy and European Space Agency (ESA)

Sources: FAA; Jonathan McDowell/planet4589.org; Roscosmos; press reports

Structural analysis:

Determination of the effects of loads on physical structures and their components.

Analysis based on:

- physical laws
- empirical knowledge of structural response of materials
- knowledge of expected loads in service

Primary effects computed

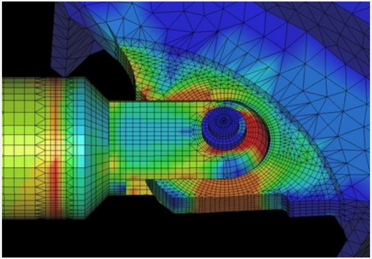
- structure's deformations
- internal stresses
- stability

Analysis results used to:

- verify structure's fitness for use (structural integrity), size components
- minimize physical tests

Disciplines involved:

- Applied mechanics
- Materials science
- Applied mathematics



Examples of engineering structures

- Civil Engineering: general buildings, bridges, dams, towers, cooling towers, offshore oil platforms
- Mechanical Engineering: ground vehicles, machinery, cranes, rollercoasters
- Aerospace Engineering: aircraft, spacecraft
- Naval Engineering: ships, submarines
- Others:
  - machinery
  - electronic components
  - medical devices

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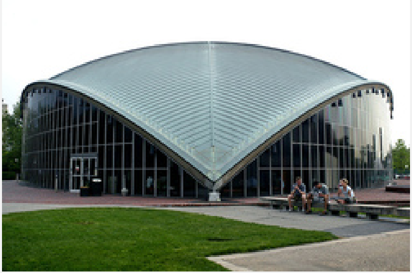
Structures as hierarchical systems

Complex structural systems are built from simple structural elements:

- linear:
  - rods
  - beams
  - struts
  - cables
- surface:
  - membranes
  - plates
  - shells
- volume: blocks, parts, ...
- Nowadays material microstructure considered part of this hierarchy



Brief History of Structural Analysis

- 1452-1519 Leonardo da Vinci
- 1638: Galileo Galilei examined the failure of simple structures
- 1660: Hooke's law by Robert Hooke
- 1687: Newton's laws of motion
- 1750: Euler-Bernoulli beam equation
- 1700-1782: Daniel Bernoulli introduced the principle of virtual work
- 1707-1783: Leonhard Euler developed the theory of buckling of columns
- 1826: Claude-Louis Navier published a treatise on the elastic behaviors of structures
- 1873: Carlo Alberto Castigliano: theorem for computing displacement as partial derivative of the strain energy
- 1936: Hardy Cross: moment distribution method
- 1941: Alexander Hrennikoff MIT D.Sc thesis: discretization of plane elasticity problems using a lattice framework
- 1942: R. Courant divided a domain into finite subregions
- 1956: R. W. Clough introduces the "finite-element method"

The role of Materials in Structural Engineering

Structural engineering requires the knowledge of materials and the quantitative characterization of its mechanical properties in order to understand how different materials support and resist loads.

Common Aerospace Structural Materials

- Aluminum alloys
- Steel
- Fiber-reinforced Composites (Glass, Carbon)
- Titanium alloys

High-temperature materials for jet engines

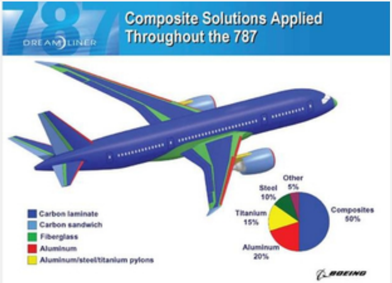
- Nickel Superalloys
- Titanium
- Thermal Barrier Coatings
- Ceramic Matrix Composites
- Intermetallics

Material advances influence structural design and functionality

1.3 Times Wider Windows

The maximum window width is 28 cm and the height is 47 cm. The windows of the Boeing 787 Dreamliner realize a stronger airframe by adopting new materials and are increased by about 1.3 times compared to those of a conventional aircraft. This allows passengers without window seats the ability to look out of windows and enjoy the outside views.

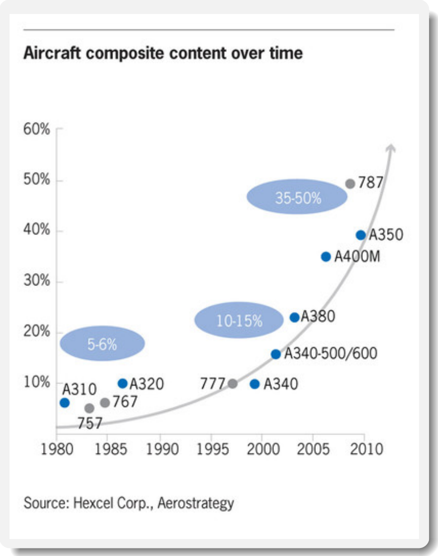
Advances in Structural Materials



Advances in Structural Materials

Source: Navy/public domain

Advances in Structural Materials



Source: Hexcel Corp., Aerostrategy

Basic material behavior relevant to structural engineering

Elasticity

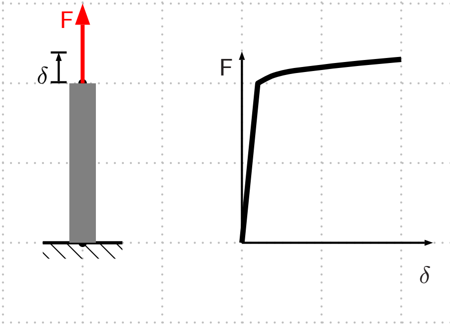
The ability of materials to deform under stress. Elastic deformations are reversible, they disappear when the stress is removed (e.g. an elastic band). A linear response between stress and strain is observed in most materials for sufficiently small deformations.

Plasticity

Permanent (inelastic) deformations arising in materials when stressed beyond a threshold.

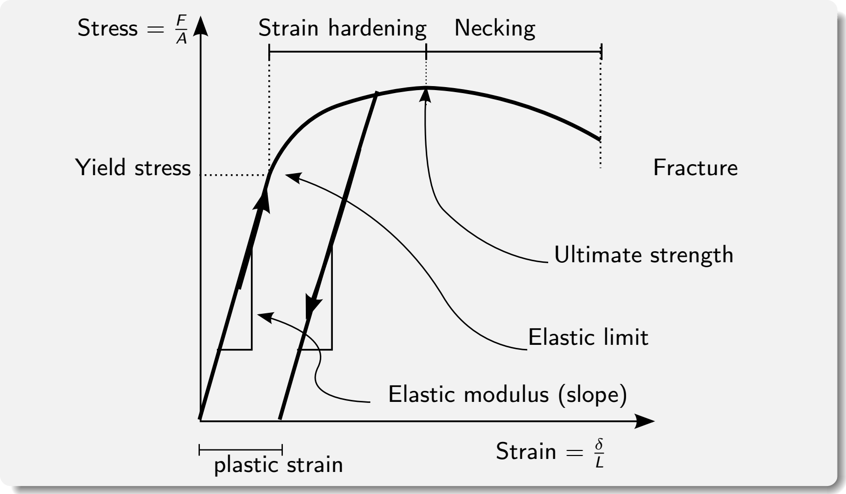
Fracture

Catastrophic failure of materials under stress, material separation.



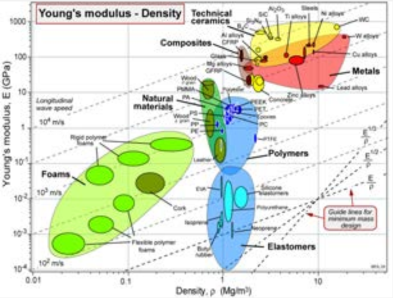
General features of a stress-strain curve

For a ductile metal:

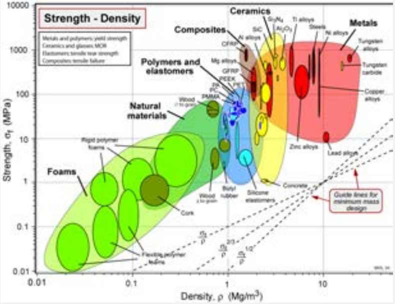


Material Selection (Ashby charts)

Stiffness vs mass density

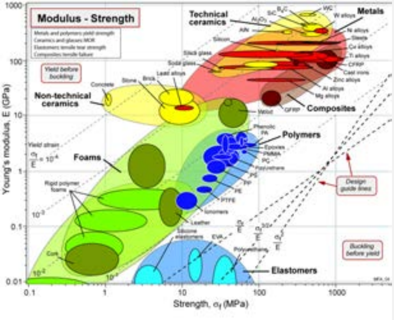


Strength vs mass density

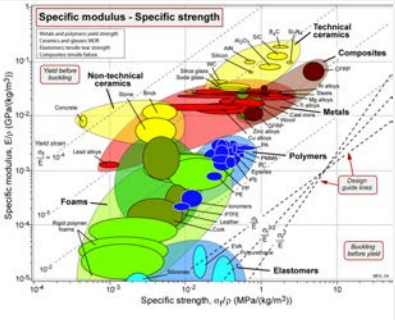


Material Selection (Ashby charts)

Stiffness vs strength

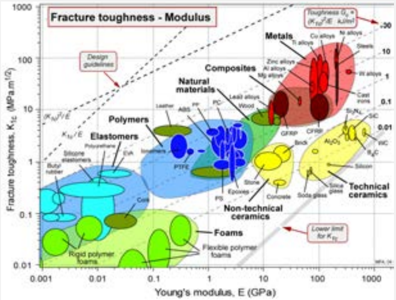


Stiffness vs strength (specific)

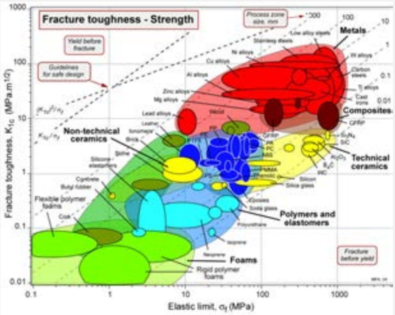


Material Selection (Ashby charts)

Fracture toughness vs modulus



Fracture toughness vs strength



Material Properties

Chemical Composition

- Al, Fe, C, Si, ...

Physical Properties

- density $[\rho] = \text{Kg m}^{-3}$
- microstructure: amorphous, crystalline: grain size, texture, composite: layup characteristics
- ...

Mechanical Properties

- Modulus of elasticity, E: $[E] = \text{GPa}$
- Poisson ratio, ν, $[\nu] = 1$
- Yield stress, σ_y: $[\sigma_y] = \text{GPa}$
- Fracture toughness, K_{Ic}, $[K_{Ic}] = \text{Pa}\sqrt{\text{m}}$
- Fatigue life, N_C, $[N_c] = 1$

Thermal properties

- Thermal expansion coefficient
- Heat capacity
- Thermal conductivity
- Melting point, glass-transition point, ...

Unified M&S Learning objectives

Students graduating from Unified will be able to:

- **use** the one-dimensional idealizations of slender members (i.e. rods, simple beams, simple columns and circular cross-section shafts) to **calculate** stress and deformation states in structures, including trusses, beams and shafts.
- **apply** the basic concepts of material properties and the underlying deformation and failure mechanisms in order to **perform** selection and preliminary sizing of the classes of structure discussed above.
- **assess** the applicability of such idealizations of materials and structures and the errors introduced in their use.

Measurable Outcomes

Students graduating from Unified will be able to:

- **Explain** the basic considerations of structural design
- **Explain** the basic assumptions underlying the idealizations of simple beams columns, trusses, circular cross-section shafts and material properties.
- **Apply** a basic physical intuition for the function and sizing of structural elements and the selection of materials for use in them.
- **Calculate** the two dimensional stress and strain state at a point given three components of stress or strain
- **Calculate** the stress and strain distributions and deformation of simple structural idealizations studied in this class
- **Design/specify** an internal structural configuration for simple trusses, beams, columns and shafts in order to meet specifed loading and deformation criteria
- **Assess** the conditions under which the idealizations studied cease to be applicable

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