16.001 Unified Engineering
Materials and Structures
Fall 2021

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Teaching Assistants: Daniel Pickard (pickard@mit.edu)
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Massachusetts Institute of Technology
Department of Aeronautics & Astronautics

September 9, 2021

Staff

Instructors:

Zack Cordero (zcordero@mit.edu)
Research interests:

- materials processing science, microstructure design, and mechanics of materials to develop novel propulsion materials and architectured materials for high-performance aerospace applications.

Office Hours: Wednesdays 3:00-5:00pm, 33-116 - Unified Student Lounge

Raúl Radovitzky (rapa@mit.edu)
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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

Outline

What is a Structure?

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

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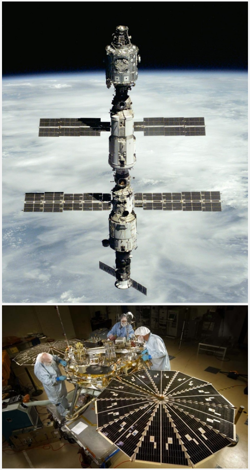
- insulate, reflect, protect
- provide comfort

Discipline concerned with the analysis, design and optimization of load-bearing structures



Structural Engineering

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Broad steps in creating a structure

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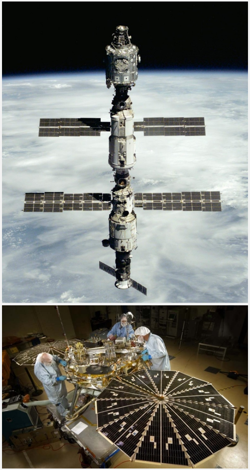
Broad steps in creating a structure

- identify loads structure will experience in its expected life



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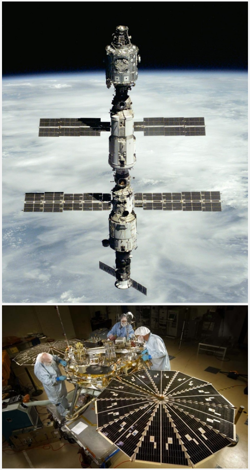
Broad steps in creating a structure

- identify loads structure will experience in its expected life
- determine suitable arrangement of structural elements



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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

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

Link to: Smithsonian video, simulation blade-off

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

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

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Disciplines involved:

- Applied mechanics
- Materials science
- Applied mathematics

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Analysis based on:

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- empirical knowledge of structural response of materials
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Primary effects computed

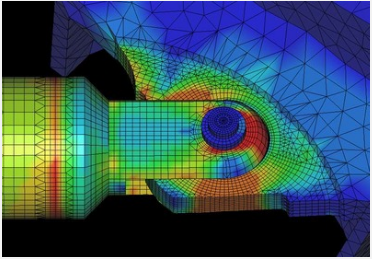
- structure's deformations
- internal stresses
- stability

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

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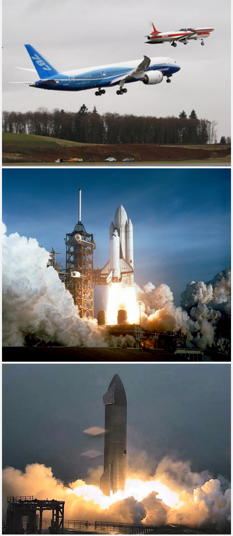
- Naval Engineering: ships, submarines



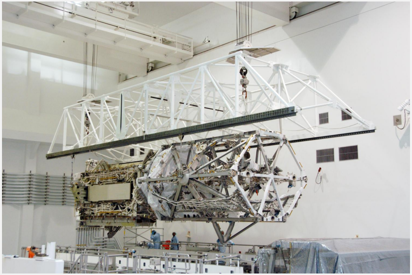
Examples of engineering structures

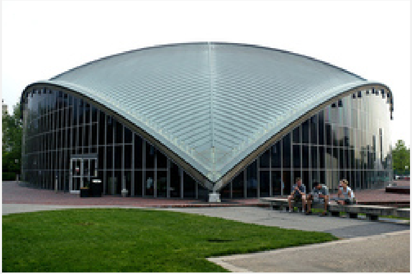
- Civil Engineering: general buildings, bridges, dams, towers, cooling towers, offshore oil platforms
- Mechanical Engineering: ground vehicles, machinery, cranes, rollercoasters
- Aerospace Engineering: aircraft, spacecraft
- Naval Engineering: ships, submarines
- Others:
  - machinery
  - electronic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

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"

Outline

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

High-temperature materials for jet engines



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High-temperature materials for jet engines

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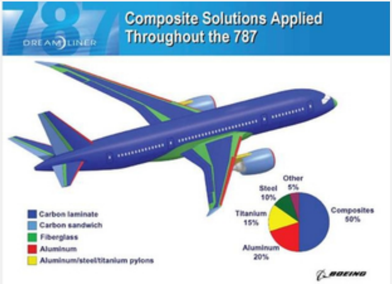
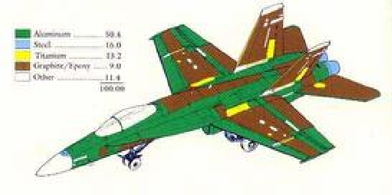
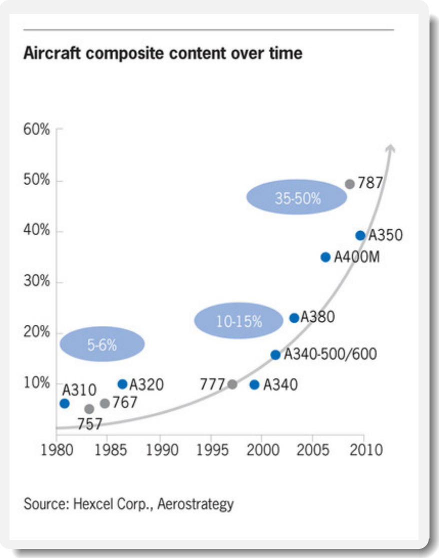
- Titanium
- Thermal Barrier Coatings
- Ceramic Matrix Composites
- Intermetallics

Material advances influence structural design and functionality

Advances in Structural Materials




Aluminum 50.4
Steel 16.0
Titanium 13.2
Graphite/Epoxy 9.0
Other 11.4
100.00


Aircraft composite content over time
60%
50%
40%
30%
20%
10%
35-50%
10-15%
5-6%
787
A350
A400M
A380
A340-500/600
A340
777
A320
A310
767
757
1980
1985
1990
1995
2000
2005
2010
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

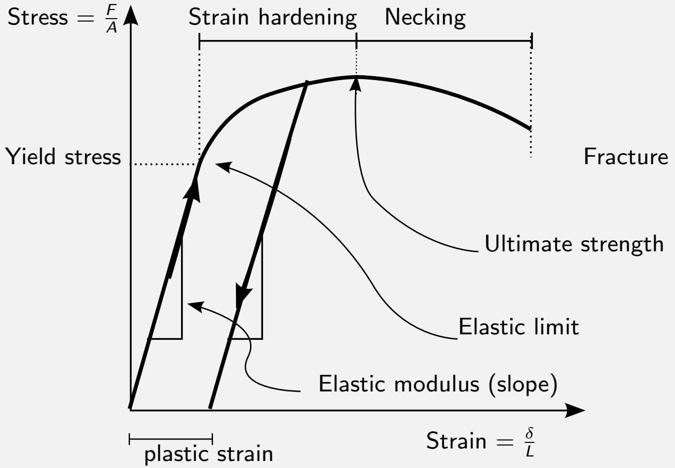
Permanent (inelastic) deformations arising in materials when stressed beyond a threshold.

Fracture

Catastrophic failure of materials under stress, material separation.

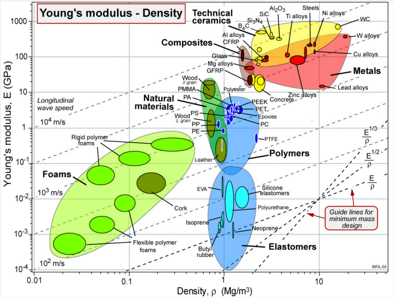
General features of a stress-strain curve

For a ductile metal:

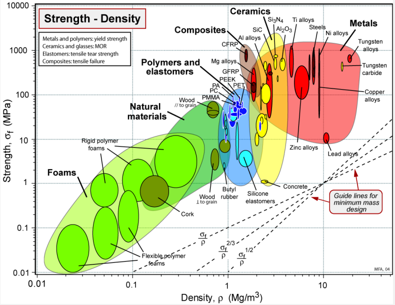


Material Selection (Ashby charts)

Stiffness vs mass density

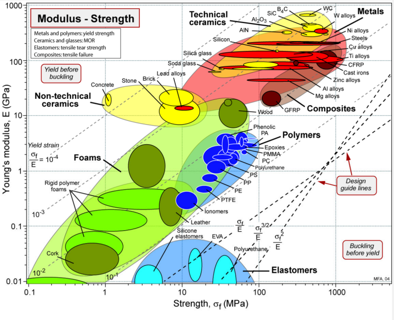


Strength vs mass density

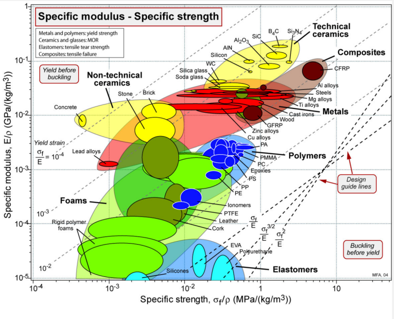


Material Selection (Ashby charts)

Stiffness vs strength

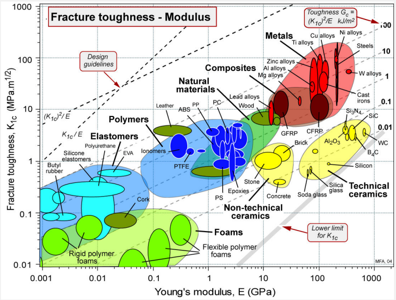


Stiffness vs strength (specific)

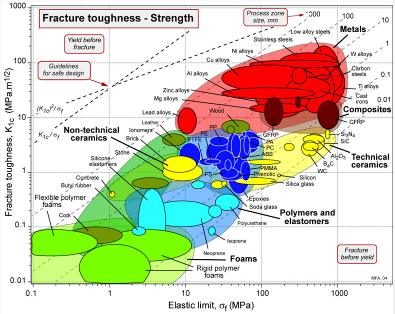


Material Selection (Ashby charts)

Fracture toughness vs modulus



Fracture toughness vs strength



Chemical Composition

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

Material Properties

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Physical Properties

- density $[\rho] = \text{Kg m}^{-3}$
- microstructure: amorphous, crystalline: grain size, texture, composite: layup characteristics
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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, $[N_c] = 1$

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Thermal properties

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

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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.

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- **assess** the applicability of such idealizations of materials and structures and the errors introduced in their use.

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- **Assess** the conditions under which the idealizations studied cease to be applicable