EPFL

Introduction to the Design of Space Mechanisms

Theme 5:

Structures – Part 1

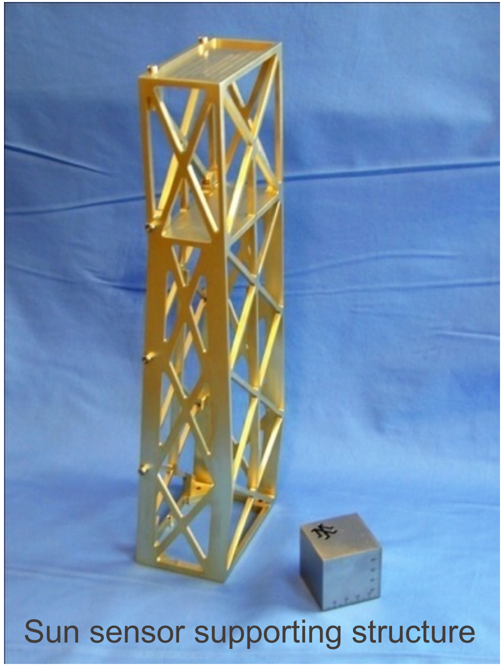
Gilles Feusier

Properties of Structures

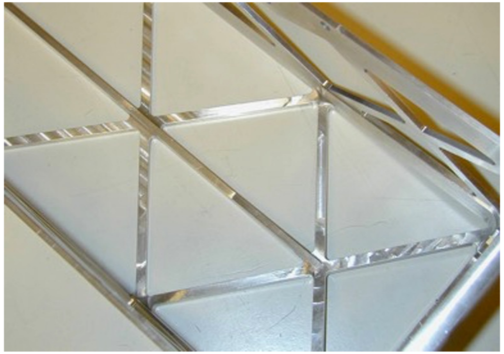
- Support the load
  - Functional loads
  - Launch loads
    - Static acceleration
    - Vibrations
    - Shocks
    - Acoustic pressure
- Limited deformation under load
  - Elastic deformation
  - Permanent deformation
    - Plasticity
    - Creep
- Limited Thermo-Elastics deformation
- Adapted interfaces
- Adapted materials
  - Temperature range
  - Environment
- Mass constrains: reducing the mass

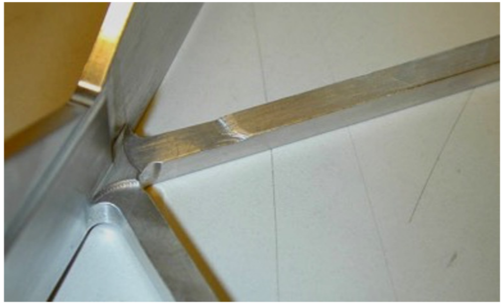
Properties of Structures

- Examples

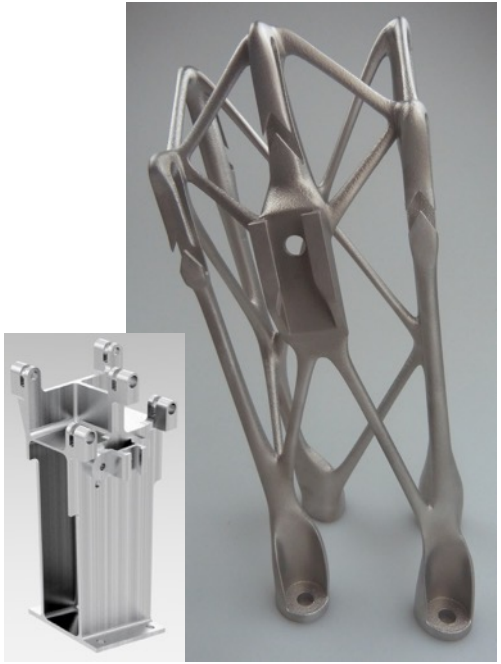


Sun sensor supporting structure





Source: Mecanex SA



Source: RUAG

Reducing the mass: material selection

- Ideal case:
  - Maximum strength
    - σ_{max} as high as possible
    - σ_{max} can be $\sigma_{0.2}$ (yield strength) or σ_u (ultimate strength)
  - Minimum mass
    - ρ minimum (low specific mass)

Note: ECSS-E-HB-32-20 Part 1A Table 1.2-1 gives some example values

→ $\frac{\sigma_{max}}{\rho}$ **as high as possible**

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→ $$\frac{\sigma_{max}}{\rho}$$ **as high as possible**

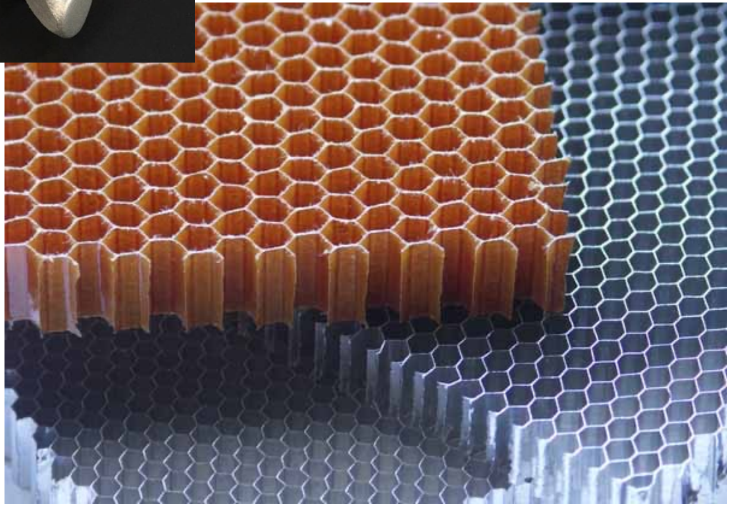
Various sources, for order of magnitude only

Material	**σ_{max} [MPa]**	**ρ [kg/m^3]**	**σ_{max} / ρ**	**Comments**
Polyimide (Vespel SP-1)	86.2	1430	0.06	@ room temperature
INCONEL 718	980	8190	0.12	@ 650°C
Beryllium	240	1844	0.13	Very high stiffness, very brittle
Al-Li 8090 T8151	370	2540	0.15	Difficult supply, low corrosion strength
High strength stainless steel (15-5-PH)	1140	7800	0.15	Metallurgical state > H1000 or limited corrosion strength
Aluminum Series 7000 T73	435	2810	0.15	Limited stress corrosion cracking strength
Stainless steel (440C)	1280	7800	0.16	
TA6V	1000	4430	0.23	Solution treated and aged
Carbon Fiber Reinforced Polymer (CFRP)	400-2800	1500-1800	0.27-1.9	Complex technology

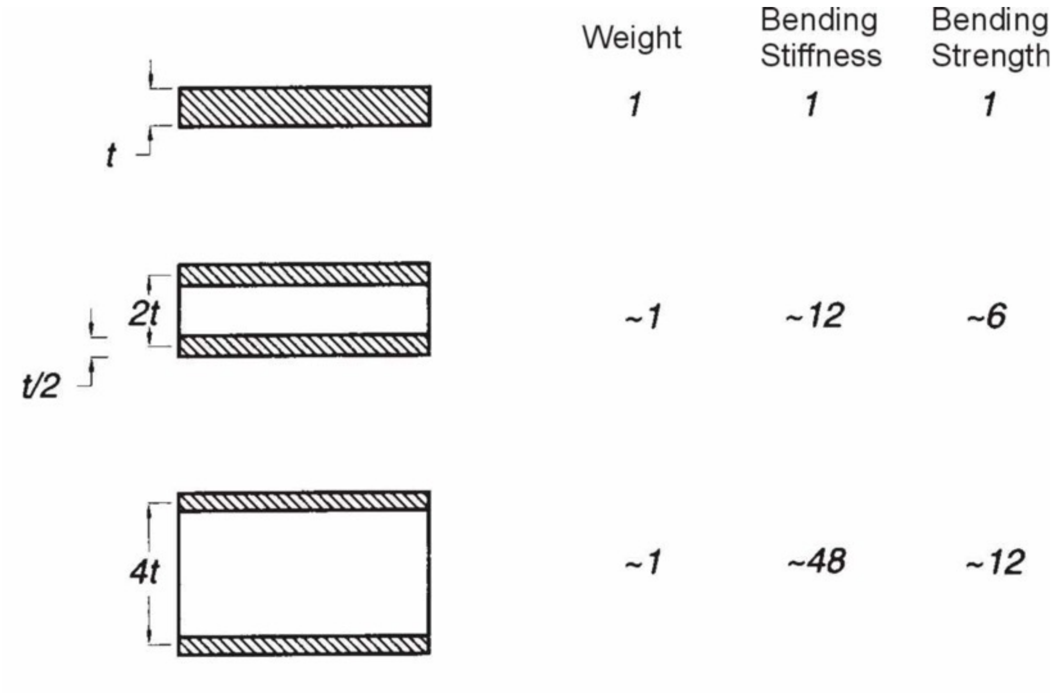
Reducing the mass: adapting the geometry

Source: M.E. Orme et al. “Additive Manufacturing of Lightweight, Optimized, Metallic Components Suitable for Space Flight”, Journal of Spacecraft and Rockets Vol. 54, No. 5, September–October 2017

- Remove excess mass
  - Machining of pockets
  - Thin parts with ribs
  - Suitable assembly methods
    - Monolithic
    - Welding
    - Riveting
    - Gluing
    - Screwing
  - Additive manufacturing
  - Use of advanced composite materials
    - Honeycomb
    - Structural polymers
    - Carbon Fiber Reinforced Polymer (CFRP)



Monolithic and sandwich cross sections



Source: ECSS-E-HB-32-20_Part3A “Structural materials handbook - Part 3: Load transfer and design of joints and design of structures”, Figure 26.2-3 (from D. Zenkert “An Introduction to sandwich construction” Chameleon Press Ltd., UK, 1995)

Sandwich structures

Disadvantages

- Complex process to master, including assembly of parts (inserts)
- Damage tolerance can be problematic and damage tolerance assessment is difficult
- Quality assurance of bonding between face sheets and core is difficult
- Difficulty of draping onto curved surfaces.
- Sensitivity to localized effects due to concentrated loads, restrictive boundary conditions, joints and geometric and material discontinuities
- Reliable non-destructive testing or evaluation can be difficult to achieve

Assembly of structures

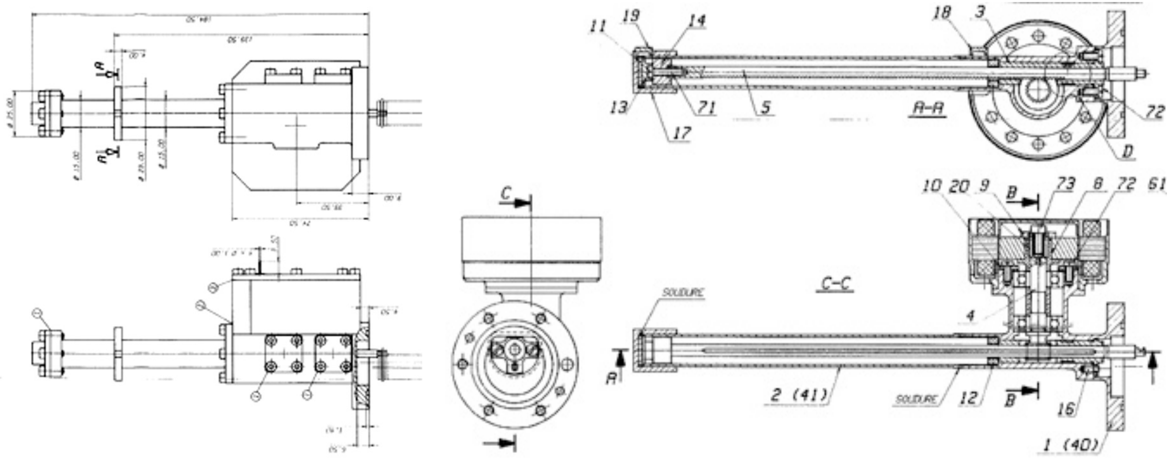
- **Monolithic**
  - Machined from billet
    - *Advantage:* no assembly elements (always critical)
    - *Drawback:* complex machining
  - Additive Manufacturing
    - *Advantage:* very complex geometry can be achieved, topology optimization, no assembly (geometry complexity ≠ manufacturing complexity)
    - *Drawback:* post-processing required, complex product assurance
- **Assembly of parts** (always critical processes requiring qualified personal)
  - **Screwing**
    - Well-known technology
    - Size (size of bolts + threaded holes + nuts)
    - Procurement, cost: manufacturing and assembly
  - **Welding**: Arc welding (TIG: Tungsten Inert Gas), EBW (Electron Beam Welding), LASER welding, Friction-stir welding …
    - Metallurgical transformation with the creation of lower strength area
    - Risk of corrosion
    - Incompatible materials (e.g. Al-Li)
  - **Riveting**
    - Highly elaborated and well-known technology (aerospace).
    - Highly dependent on qualified personal
    - Risk of stress corrosion cracking. Surface finish and cleanliness are key
  - **Gluing**
    - Highly dependent on surface finish (cleanliness, presence of a potential primer, surface roughness, …)
    - Selection of the glues with respect to the use
    - Risks during operations: aging under radiations, thermal degradation, softening (e.g. glass transition temperature, chemical modifications …)…

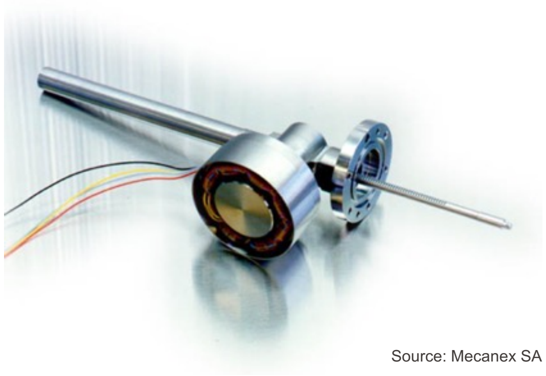
Source: RUAG Group

Source: ESA–G. Porter

Assembly of structures

- Example of assembly
  - **Filter mechanism** (FIM) for an experiment on **Cassigny-Huygens** mission: the Aerosol Collector Pyrolyser (ACP)
    - Engineering Model (EM): assembled with screws
      Mass: 750g
    - Flight Model (FM): assembled by LASER welding
      Mass: 450g
    - Complex disassembly, but not necessary for the application

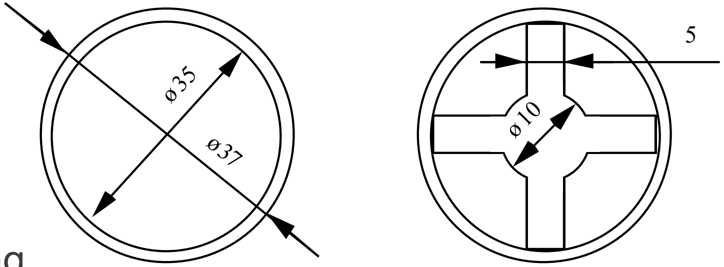


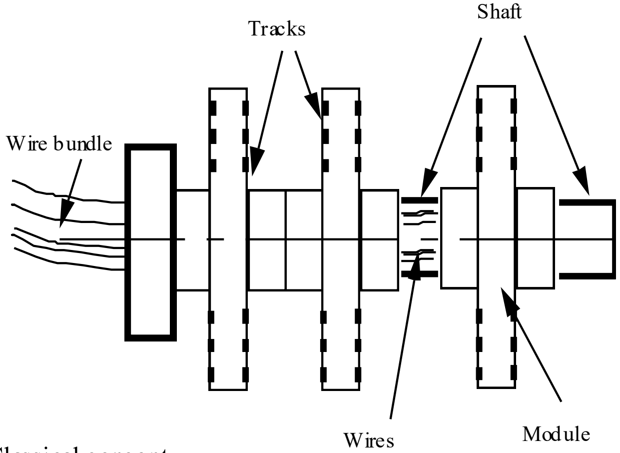


Source: Mecanex SA

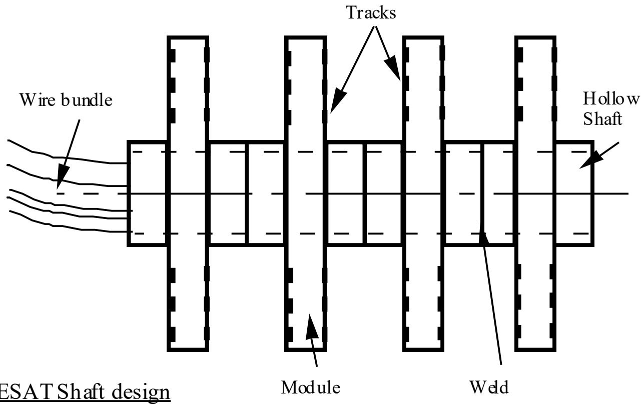
Assembly of structures

- Example of assembly
  - Welded slipring axis
    - Thin walls (1mm)
    - Reduced mass
    - Increase available volume for cable routing
    - Mechanical strength high enough for the application





Classical concept



MESAT Shaft design

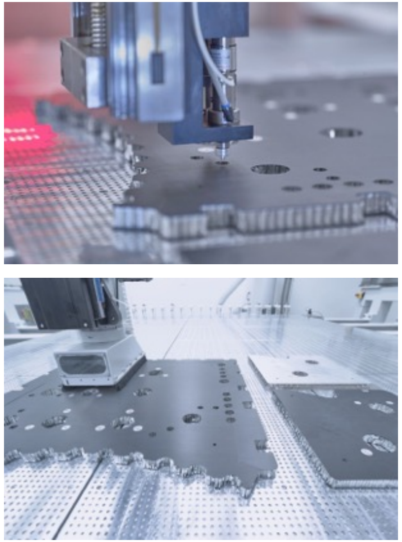
Source: Mecanex SA

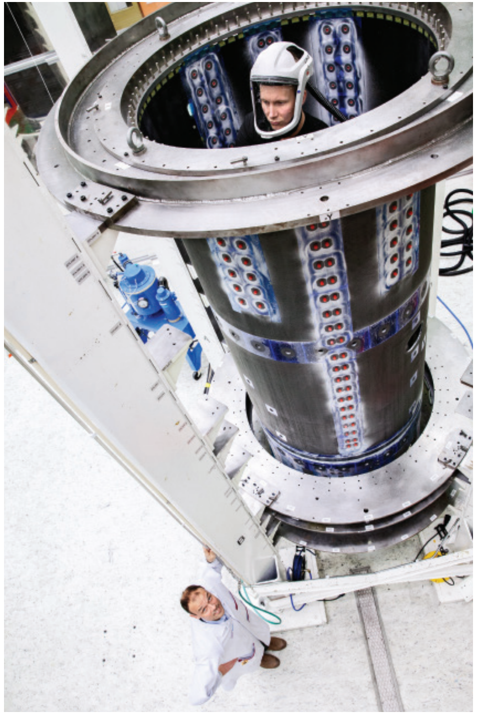
Assembly of structures

- Example of assembly
  - Inserts and threaded inserts glued into a CFRP honeycomb structure

Hot-bonded inserts on Sentinel-5 P

Source: APCO Technologies





Source: RUAG Space

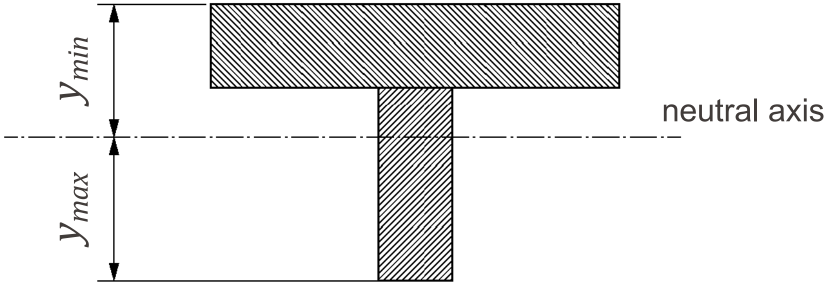
Describe possible structures

- Turn to your neighbours
- **How wo do you create the structure supporting e.g. the antenna in the proposed “mini-project”? How would you optimize it (reducing mass, increasing stiffness, …)?**
- **Discuss the technical possibilities (geometries, materials, …)?**
- 5 minutes discussion
- Share your outcomes
- You can make sketches!

Ribs

- Maximum stress

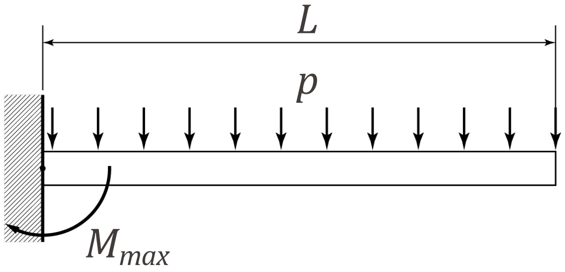
$$\sigma_{max} = \frac{M_{max}}{I} y_{max}$$



- Where: M_{max} maximum bending moment
  I area moment of inertia
  y_{max} maximum distance to neutral axis

- For a cantilever beam with a length L and with a uniform load p:

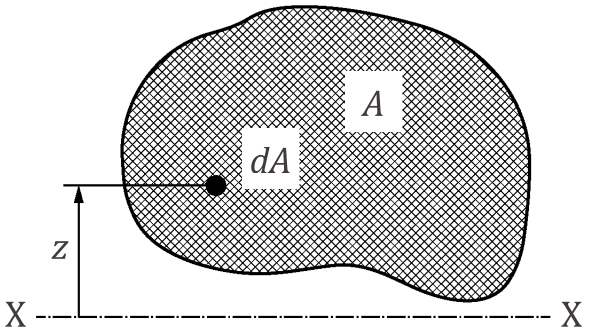
$$M_{max} = \frac{p \cdot L^2}{2}$$



Ribs

- Area moment of inertia

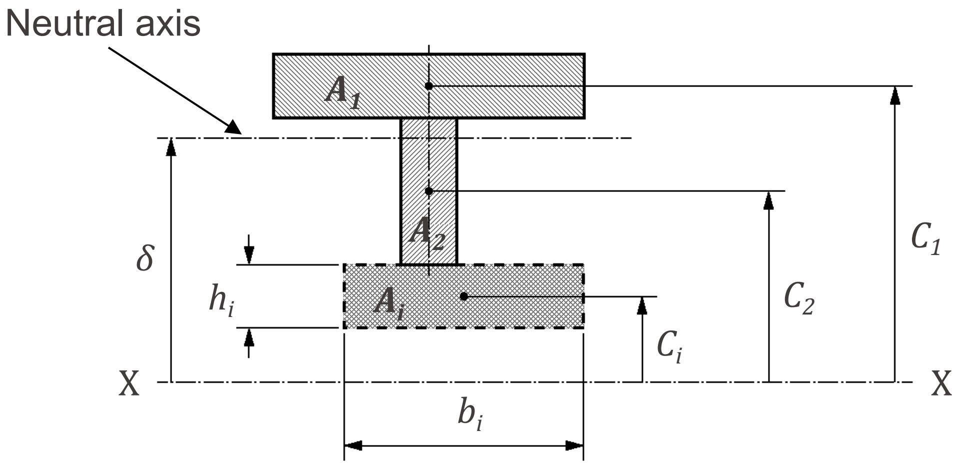
$$I = \int_A z^2 dA$$



Parallel axis theorem:

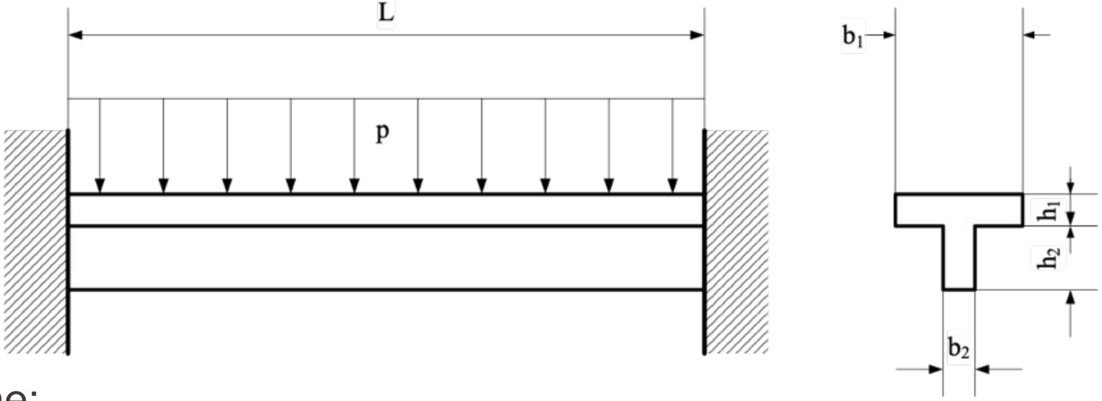
$$I = \sum_i \left(C_i^2 \cdot A_i + I_i\right)$$

$$I_i = \frac{b_i \cdot h_i^3}{12}$$



Ribs

- Example of ribbed beam
  - Constant section
  - Fixed at both ends
  - Load uniformly distributed



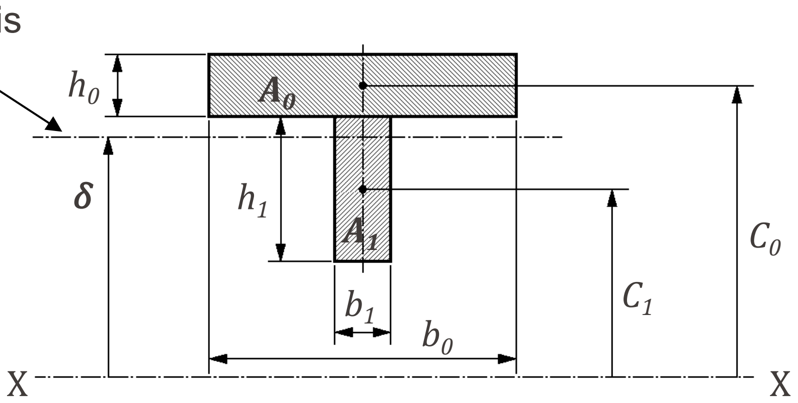
- Determine:
  - Thickness of a non-ribbed beam with same deformation
  - Mass ratio of both ribbed/non-ribbed beams
  - Maximum stress in both cases

Ribs

- Example
  - **Ribbed beam** (A_0; A_1) with respect to the neutral axis:

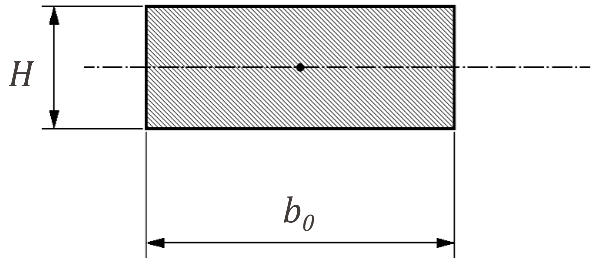
$$I_{n\_a} = \sum_{i=0}^{1} \left\{ \frac{b_i \cdot h_i^3}{12} + (C_i - \delta)^2 \cdot A_i \right\}$$

$$\delta = \frac{\sum_i A_i \cdot C_i}{\sum_i A_i}$$



  - **Non-ribbed beam** (same width, same inertia):

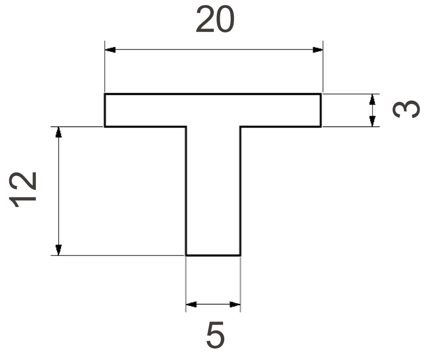
$$H = \sqrt[3]{\frac{12 \cdot I_{n\_a}}{b_0}}$$



  - Mass ratio of both beam types:

$$\Lambda = \frac{\sum_{i=0}^{1} A_i}{b_0 \cdot H}$$

Ribs

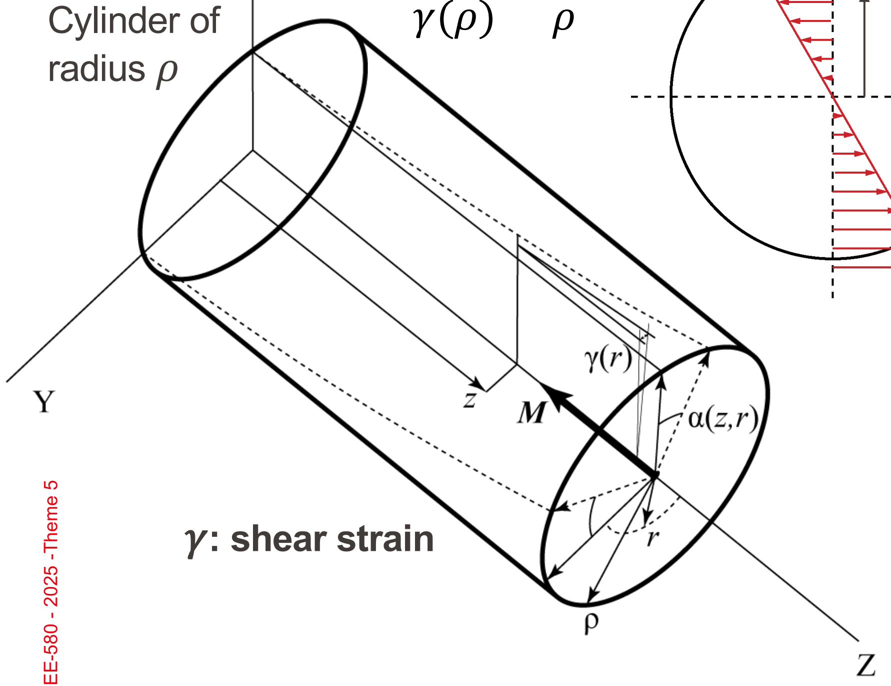


- Numerical application
  - b_1 = 20mm h_1 = 3mm
  - b_2 = 5mm h_2 = 12mm
- Area moment of inertia wrt neutral axis
  - I = 2453mm^4
- Thickness of the non-ribbed beam (rectangular) with same width and same inertia I:
  - H = 11.37mm
- Mass ratio:
  - ***M(ribbed) / M(rectangular)* = 0.53**
- Maximum stresses induced by load p_T (own mass of ribbed beam)
  - L = 250mm, p_T = 10N/m (Ni alloy beam, ρ = 8'500kg/m^3)
  - Ribbed beam: $\boldsymbol{\sigma_{max\_rib}}$ = **1.24 MPa**
  - Equivalent rectangular beam: $\boldsymbol{\sigma_{max\_rect}}$ = **1.37 MPa**
- Rib has a positive effect, but other effects shall be carefully assessed:
  - Torsion
  - Buckling

Torsion

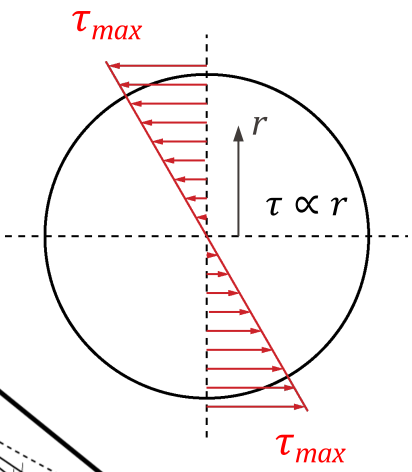
Cylinder of radius ρ

$$\frac{\gamma(r)}{\gamma(\rho)} = \frac{r}{\rho}$$



γ: **shear strain**

pure shear stresses τ



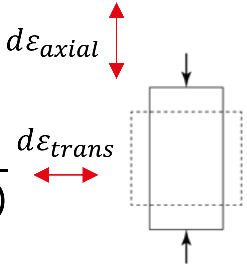
For **low torsion** angle α (Euler-Bernoulli theory)

$$d\alpha = \frac{\gamma(\rho)}{\rho} dz$$

$$\alpha(z) = \frac{M \cdot z}{I_t \cdot G}$$

Where:

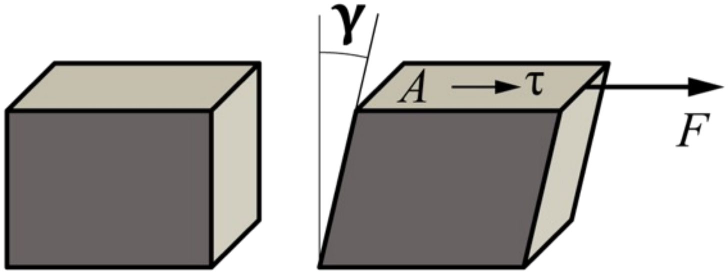
Shear modulus $G = \frac{E}{2(1+\mu)}$



I_t: polar moment of inertia

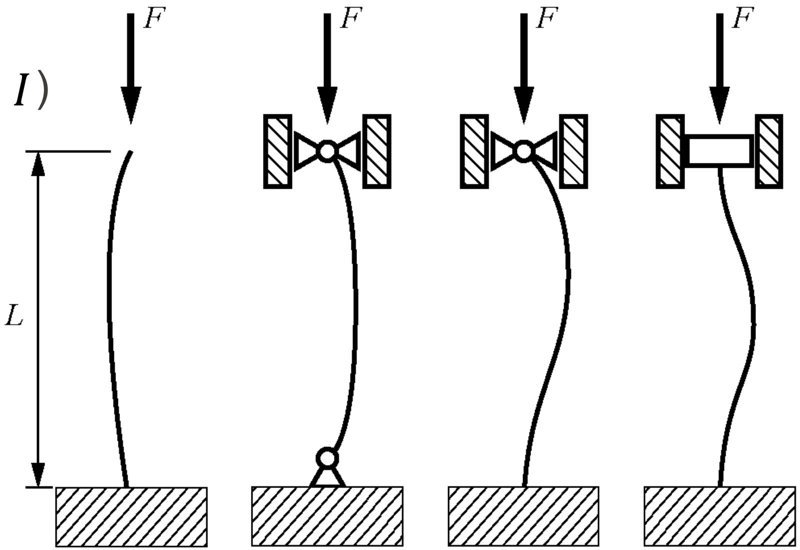
Poisson ratio: $\mu = -\frac{d\varepsilon_{trans}}{d\varepsilon_{axial}}$

Hooke's law for a **shear stress**: $\boldsymbol{\tau} = G \cdot \gamma$



Buckling

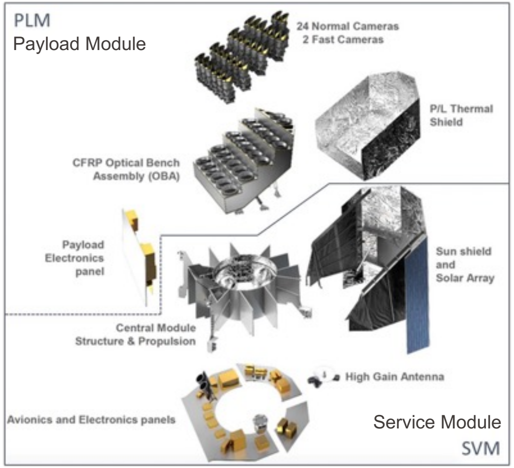
- Beam under compressive load
- It exists a limit force F_{lim} over which there is buckling, which depends on:
  - The length of the beam L
  - The cross-section of the beam ($F_{lim} \propto I$)
  - The material (Young's modulus)
  - How the beam is fixed
- Buckling appears abruptly and unexpectedly

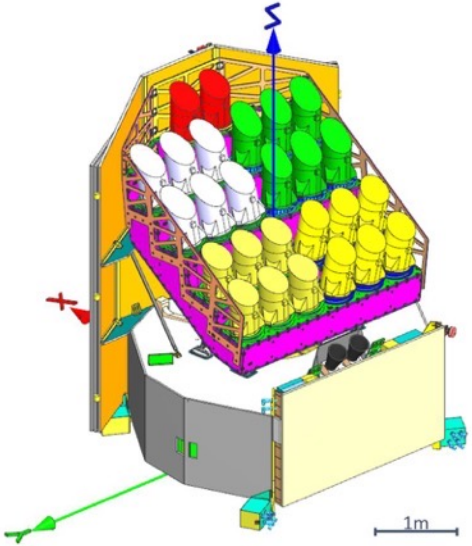


Thermo-Elastic Deformations

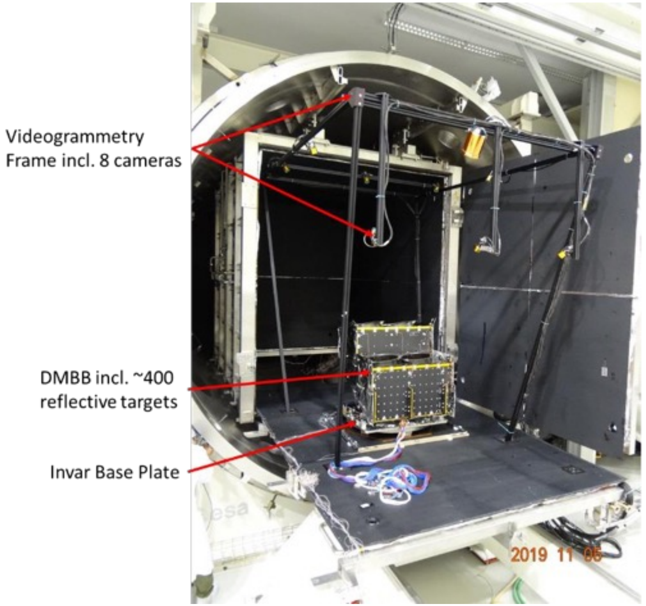
Example: PLATO Spacecraft with 26 Cameras

Source: J.Junker et al. “PLATO Spacecraft: Thermo-elastic Distortion Verification Concept dnd Demonstrator Tests”, Proceedings of ECSSMET 2021





Videogrammetry



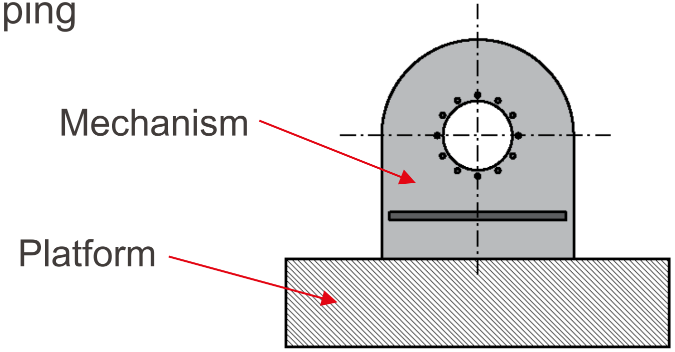
Suggested reference on TE analysis:
S. Appel & J. Wijker “*Simulation of Thermoelastic Behaviour of Spacecraft Structures –Fundamentals and Recommendations*”, Springer (2022), Switzerland

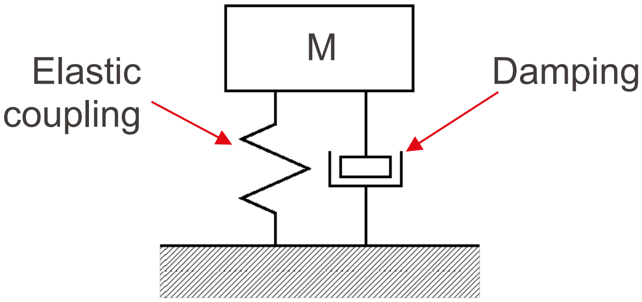
Vibration loads

- The mechanism is attached to a platform
  - The level of vibration is imposed by the platform

→ Specified spectral density

  - The mechanism react to the vibrations (resonator)
    - Eigenfrequencies
      - Several vibration modes
    - Amplification of the movement at certain frequencies (overload)
    - Damping





Theme 5 Summary

- Roles of structures
- Challenges of structures
  - Strength, including buckling
  - Mass
  - Deformations, including thermo-elastic deformations
- How to create structures, how to improve structures

In two weeks

- Theme 5 – Structures (continued): vibrations

Note:

- Mini Project part 2 Architecture: functions and components
  (cf. EE580_MP2_2025_v1 Architecture.pdf)
  Due date: **April 10th, 11:00**