Space structures

1. Mechanical behaviour of structural materials and structures for space

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THE STRUCTURAL SYSTEM OF A SPACECRAFT

Structure: set of mechanical components or assemblies designed to sustain loads or pressures, provide stiffness or stability or provide support or containment.

ECSS 30 2b Definition

The structural system of a spacecraft has three main functions:

1. To provide the support of all the other subsystem and materialize the geometry of the spacecraft and its payloads;

2. To guarantee the necessary STRENGTH to survive all phases of the spacecraft life (in particular the most critical: e.g. the launch) without failures.

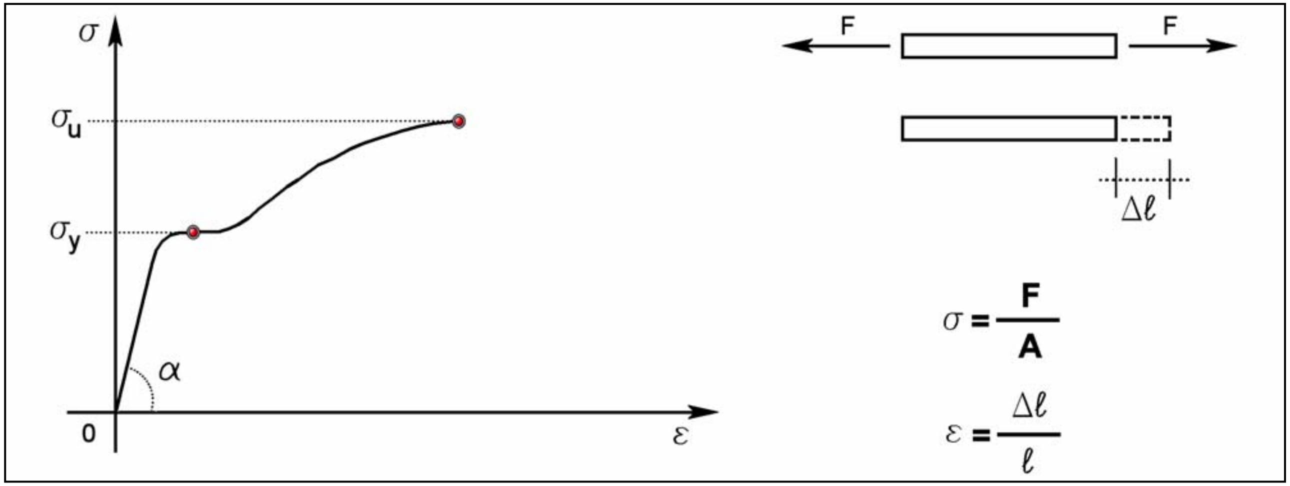
THE STRUCTURAL SYSTEM OF A SPACECRAFT (2)

3. To keep the structural STIFFNESS in certain limits to guarantee the operational functionality of the overall system and avoid coupled resonant responses (e.g. between a satellite and its launcher).

   Since the cost of mass is very critical in a space mission, the structural system should be optimized with respect to mass both in terms of material and in terms of the optimal structural geometries.

Structural problems affect also other subsystems (e.g. propulsion, attitude and orbital control, on board data handling, TTC) and the payload itself. In fact every component of a spacecraft needs to withstand the mission environment and a structural failure could occur in a component of the system and might be critical for the success of the mission.

FORCE / DISPLACEMENT DIAGRAM OF A BAR IN TENSION



A metallic material has constitutive law characterized by an elastic range up until a yield limit, then a plastic phase up until an ultimate limit σ_u (STRENGTH).

Elastic behaviour: the structural systems subjected to an external loading progressively deforms and recovers its original shape returning back all the energy that was encorporated during the loading phase.

HOOKE'S LAW

A linear behaviour characterizes most of structural materials; in the 1D case:

$$\sigma = E\,\varepsilon$$

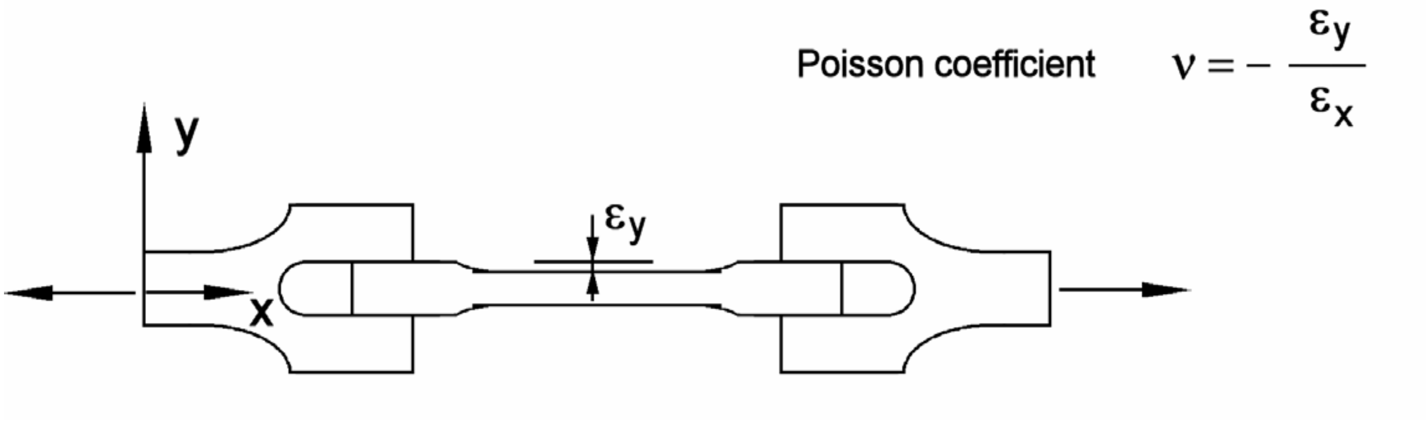
Hooke's Law

$$E = \tan \alpha$$

E: Young's modulus (STIFFNESS).

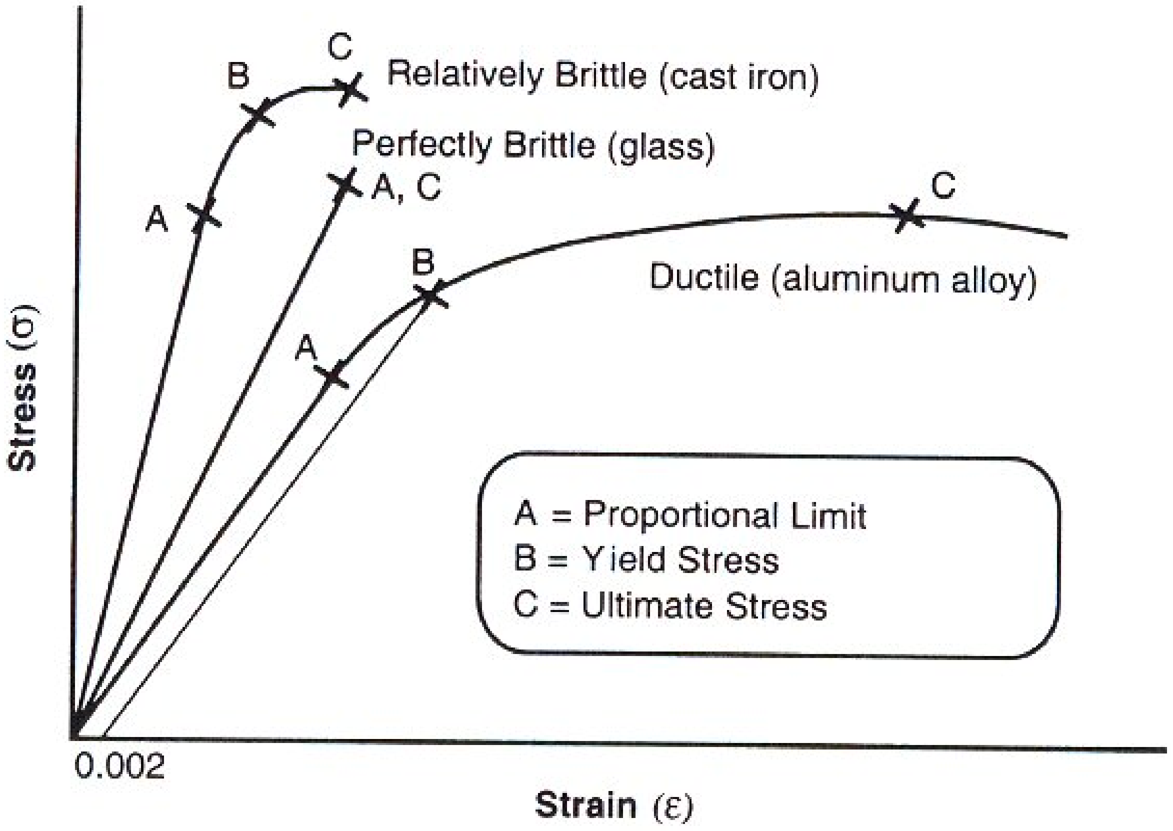
In practice a unit load is applied to a bar ad the deformation is measured: the inverse of such a value is the Young's modulus.

During the loading of the bar its section shrinks:



Poisson coefficient $\nu = -\dfrac{\varepsilon_y}{\varepsilon_x}$

DUCTILE AND BRITTLE MATERIALS

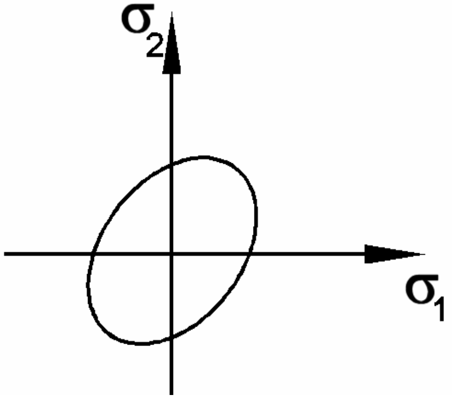


A = Proportional Limit
B = Yield Stress
C = Ultimate Stress

FAILURE CRITERIA

- In presence of biaxial loading the failure can occur at a value less than the uniaxial failure load.
- Relations between the stress components express the condition of failure in presence of a multiaxial loading (VON MISES, TRESCA CRITERIA). Special care should be devoted to cases of anisotropic material (e.g. carbon fiber reinforced plastics).

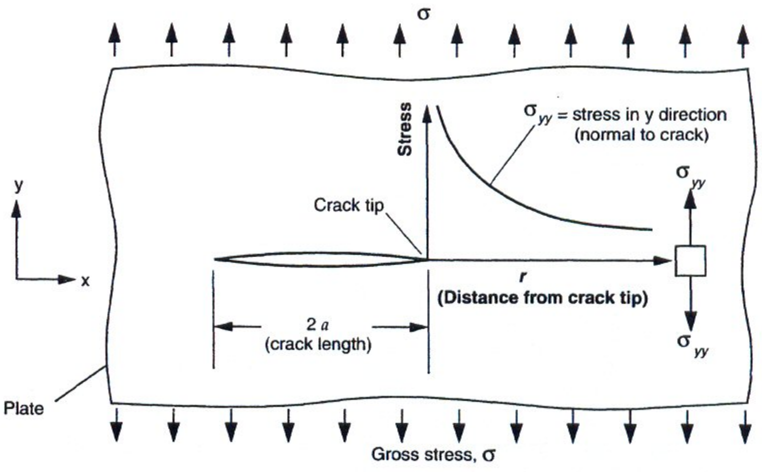
Von Mises failure criterion (2D)



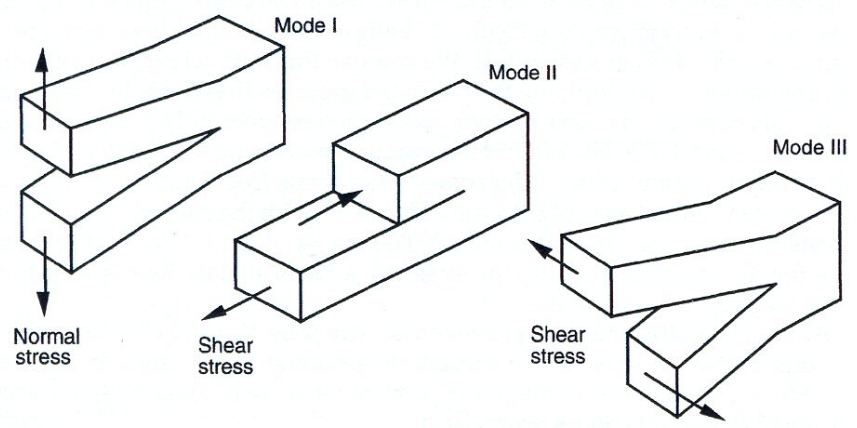
$$\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 = \sigma_{u\,max}^2$$

σ_1 σ_2 principal stresses

FRACTURE



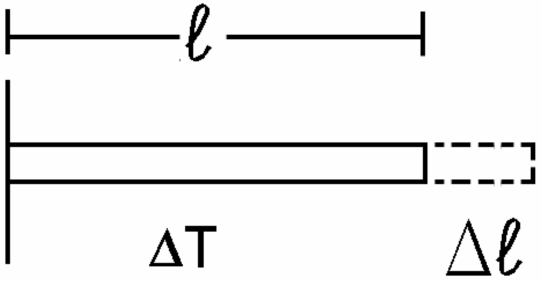
Distribution of Stress Normal to a Through Crack in a Plate.



Fracture has to be evaluated as one of the main failure mechanisms in a structural material. As well known crack opening could occur according to different opening modes, regulated by different critical intensity factor. For composite materials openings could occurr due to voids encapsulated between layers, creating an artificial delamination. Delamination is also a possible failure mode of composites.

THERMOELASTIC BEHAVIOUR

Structures (generally) expand when heated



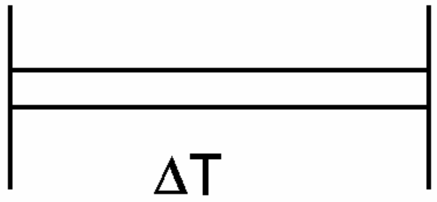
$$\varepsilon^{term} = \alpha\,\Delta T$$

$$\varepsilon^{tot} = \frac{\Delta\ell}{\ell}$$

$$\varepsilon^{tot} = \varepsilon^{term}$$

α **expansion coefficient**

ΔT jump of temperature at a point



$$\varepsilon^{term} = \alpha\,\Delta T$$

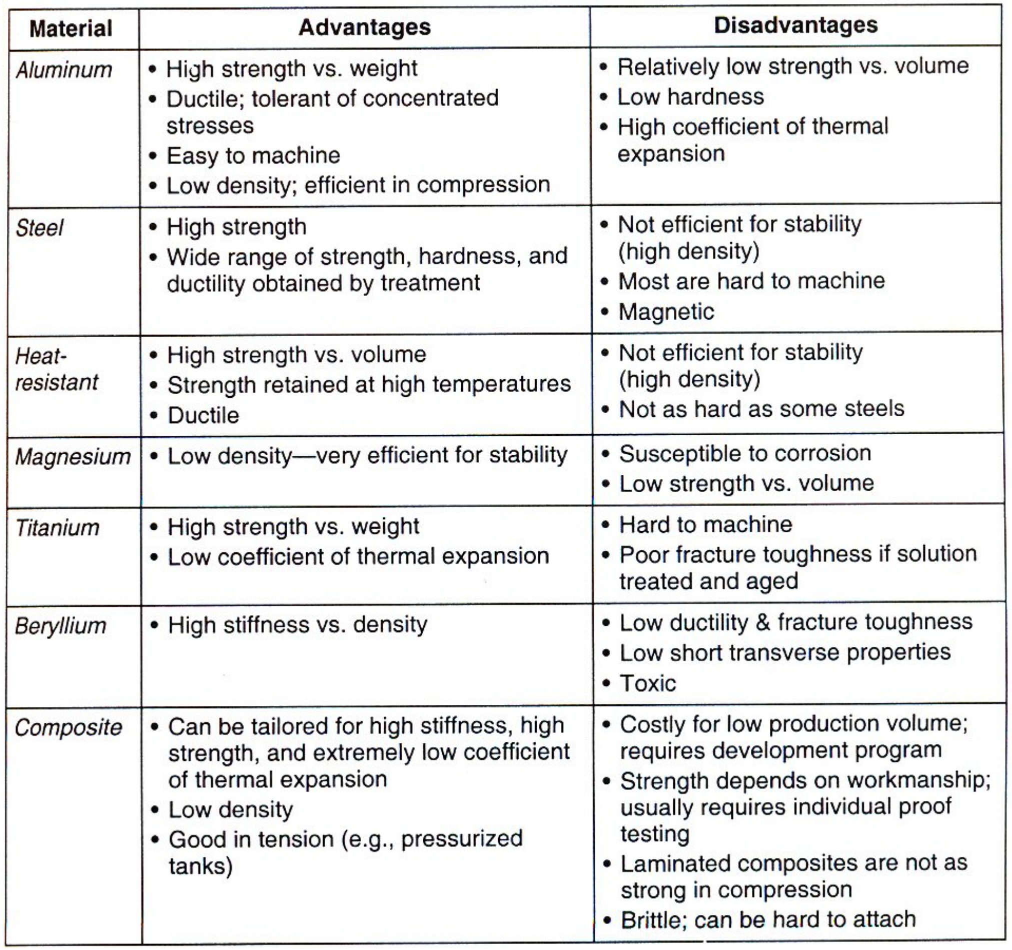
$$\varepsilon^{tot} = \frac{\Delta\ell}{\ell} = 0 = \varepsilon^{term} + \varepsilon^{mecc}$$

$$\varepsilon^{mecc} = -\,\alpha\,\Delta T = \frac{\sigma}{E}$$

$$\sigma = -\,\alpha\,E\,\Delta T$$

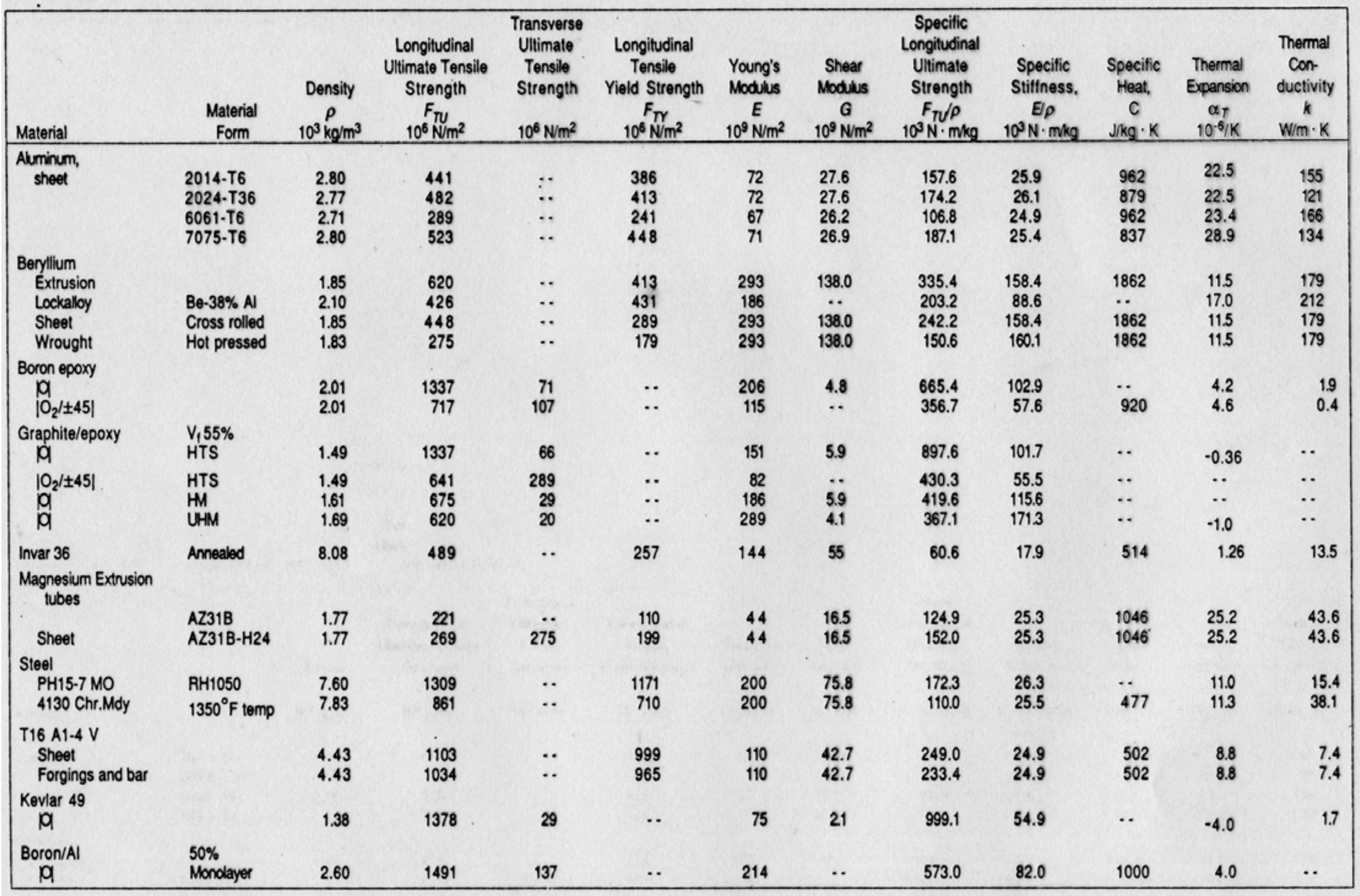
Stress produced by thermal action

TYPICAL FEATURES
OF STRUCTURAL MATERIALS FOR SPACE APPLICATIONS



Material	Advantages	Disadvantages
Aluminum	• High strength vs. weight • Ductile; tolerant of concentrated stresses • Easy to machine • Low density; efficient in compression	• Relatively low strength vs. volume • Low hardness • High coefficient of thermal expansion
Steel	• High strength • Wide range of strength, hardness, and ductility obtained by treatment	• Not efficient for stability (high density) • Most are hard to machine • Magnetic
Heat-resistant	• High strength vs. volume • Strength retained at high temperatures • Ductile	• Not efficient for stability (high density) • Not as hard as some steels
Magnesium	• Low density—very efficient for stability	• Susceptible to corrosion • Low strength vs. volume
Titanium	• High strength vs. weight • Low coefficient of thermal expansion	• Hard to machine • Poor fracture toughness if solution treated and aged
Beryllium	• High stiffness vs. density	• Low ductility & fracture toughness • Low short transverse properties • Toxic
Composite	• Can be tailored for high stiffness, high strength, and extremely low coefficient of thermal expansion • Low density • Good in tension (e.g., pressurized tanks)	• Costly for low production volume; requires development program • Strength depends on workmanship; usually requires individual proof testing • Laminated composites are not as strong in compression • Brittle; can be hard to attach

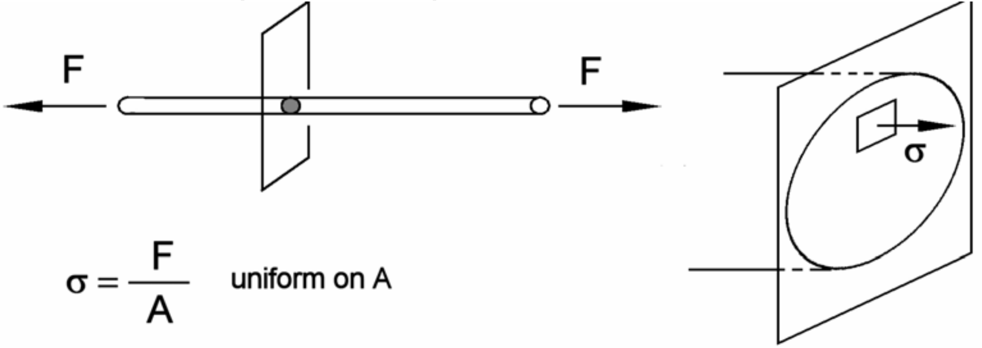
TYPICAL CHARACTERISTIC OF STRUCTURAL MATERIALS



Material	Material Form	Density ρ 10^3 kg/m^3	Longitudinal Ultimate Tensile Strength F_{TU} 10^6 N/m^2	Transverse Ultimate Tensile Strength 10^6 N/m^2	Longitudinal Tensile Yield Strength F_{TY} 10^6 N/m^2	Young's Modulus E 10^9 N/m^2	Shear Modulus G 10^9 N/m^2	Specific Longitudinal Ultimate Strength F_{TU}/ρ 10^3 N · m/kg	Specific Stiffness, E/ρ 10^3 N · m/kg	Specific Heat, C J/kg · K	Thermal Expansion α_T 10^{-6}/K	Thermal Con-ductivity k W/m · K
Aluminum,												
sheet	2014-T6	2.80	441	--	386	72	27.6	157.6	25.9	962	22.5	155
	2024-T36	2.77	482	--	413	72	27.6	174.2	26.1	879	22.5	121
	6061-T6	2.71	289	--	241	67	26.2	106.8	24.9	962	23.4	166
	7075-T6	2.80	523	--	448	71	26.9	187.1	25.4	837	28.9	134
Beryllium												
Extrusion		1.85	620	--	413	293	138.0	335.4	158.4	1862	11.5	179
Lockalloy	Be-38% Al	2.10	426	--	431	186	--	203.2	88.6	--	17.0	212
Sheet	Cross rolled	1.85	448	--	289	293	138.0	242.2	158.4	1862	11.5	179
Wrought	Hot pressed	1.83	275	--	179	293	138.0	150.6	160.1	1862	11.5	179
Boron epoxy												
|0|		2.01	1337	71	--	206	4.8	665.4	102.9	--	4.2	1.9
|0_2/±45|		2.01	717	107	--	115	--	356.7	57.6	920	4.6	0.4
Graphite/epoxy	V_f 55%											
|0|	HTS	1.49	1337	66	--	151	5.9	897.6	101.7	--	-0.36	--
|0_2/±45|	HTS	1.49	641	289	--	82	--	430.3	55.5	--	--	--
|0|	HM	1.61	675	29	--	186	5.9	419.6	115.6	--	--	--
|0|	UHM	1.69	620	20	--	289	4.1	367.1	171.3	--	-1.0	--
Invar 36	Annealed	8.08	489	--	257	144	55	60.6	17.9	514	1.26	13.5
Magnesium Extrusion tubes												
	AZ31B	1.77	221	--	110	44	16.5	124.9	25.3	1046	25.2	43.6
Sheet	AZ31B-H24	1.77	269	275	199	44	16.5	152.0	25.3	1046	25.2	43.6
Steel												
PH15-7 MO	RH1050	7.60	1309	--	1171	200	75.8	172.3	26.3	--	11.0	15.4
4130 Chr.Mdy	1350°F temp	7.83	861	--	710	200	75.8	110.0	25.5	477	11.3	38.1
T16 A1-4 V												
Sheet		4.43	1103	--	999	110	42.7	249.0	24.9	502	8.8	7.4
Forgings and bar		4.43	1034	--	965	110	42.7	233.4	24.9	502	8.8	7.4
Kevlar 49												
|0|		1.38	1378	29	--	75	21	999.1	54.9	--	-4.0	1.7
Boron/Al	50%											
|0|	Monolayer	2.60	1491	137	--	214	--	573.0	82.0	1000	4.0	--

STRUCTURAL BEHAVIOUR: BAR IN TENSION

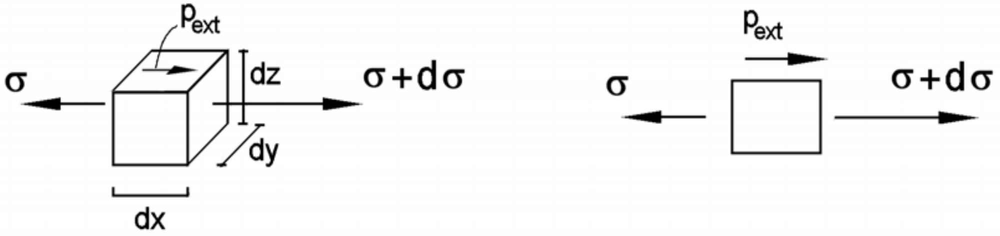
Basic experiment: a cable (or a bar) in tension



$$\sigma = \frac{F}{A} \quad \text{uniform on A}$$

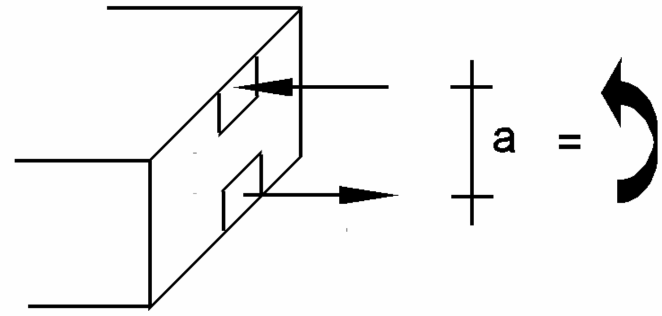
$$F = \sigma A = \int_A \sigma \, dA$$

Equilibrium of the infinitesimal element

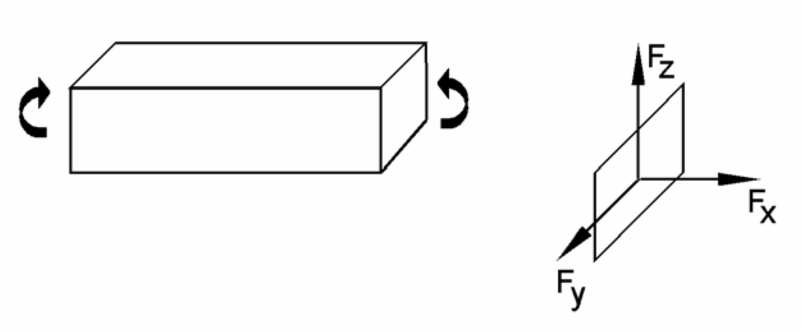


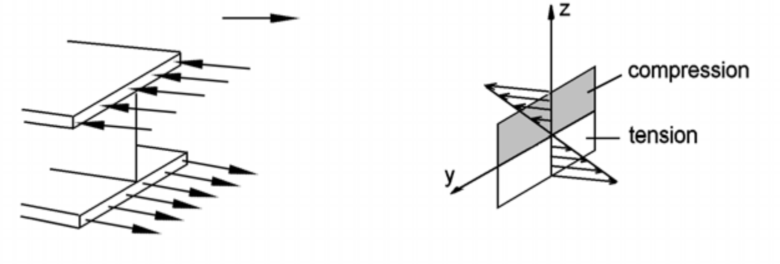
$$-\sigma \, dydz + p dxdydz + \sigma \, dydz + \frac{d\sigma}{dx} dxdydz = 0 \qquad \frac{d\sigma}{dx} = -p$$

STRUCTURAL BEHAVIOUR: PURE BENDING OF A BEAM



In order to produce a moment, σ has to vary along the section



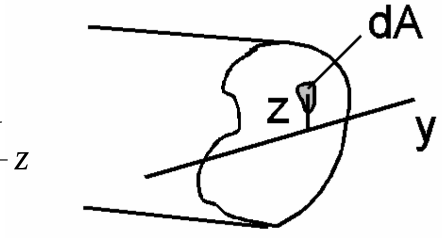


Best use of material: the optimal section is a double T

I Moment of inertia around y

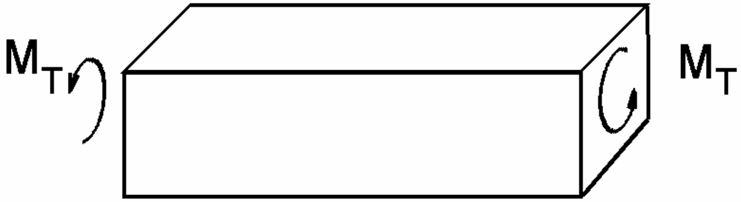
The distribution of σ is linear along the thickness.

$$\sigma = \frac{M}{I} z$$

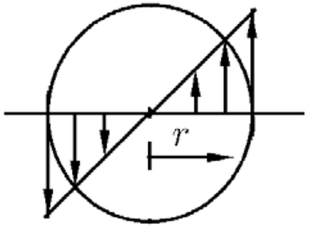


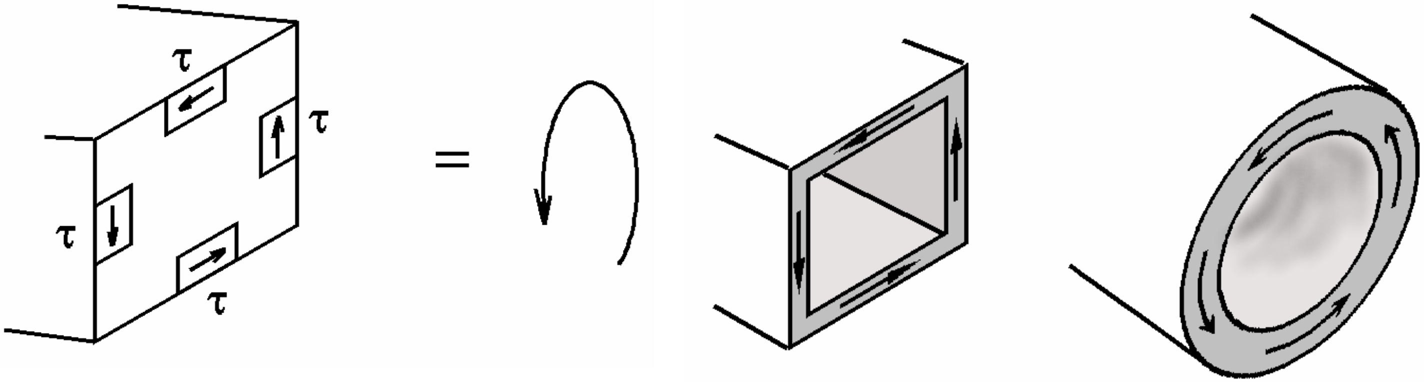
STRUCTURAL BEHAVIOUR: TORSION OF A BEAM

To produce a torque M_T the direction of the shear stress has to vary along the section



In a way similar to the bending case it can be shown that the best section has a circular thin walled section





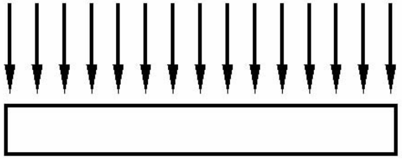
$$\tau = \frac{M_T}{\mathcal{I}_p} r \qquad (*)$$

$$\mathcal{I}_p = \int_A r^2 dA$$

*(Not applicable for not circular section)

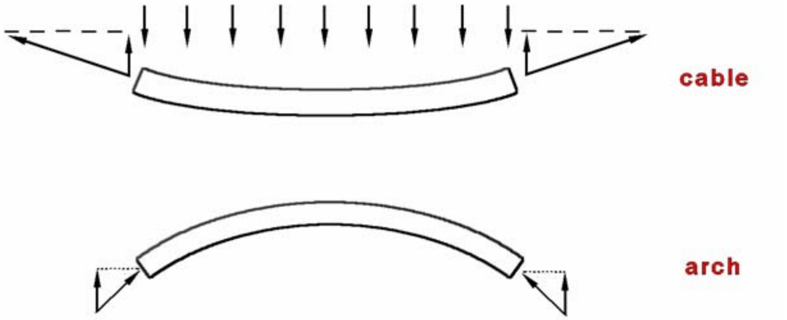
MEMBRANE AND FLEXURAL BEHAVIOUR

How can lateral loads be sustained by a unidimensional structure?

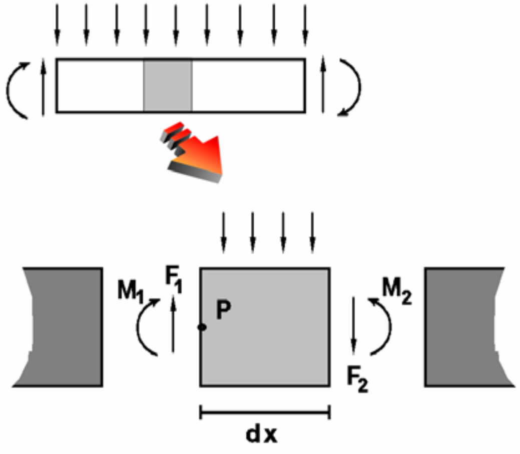


membrane

Shear + bending



Variation of geometry but uniform σ on the section



$$F_2 = F_1 + \frac{dF_1}{dx}dx$$

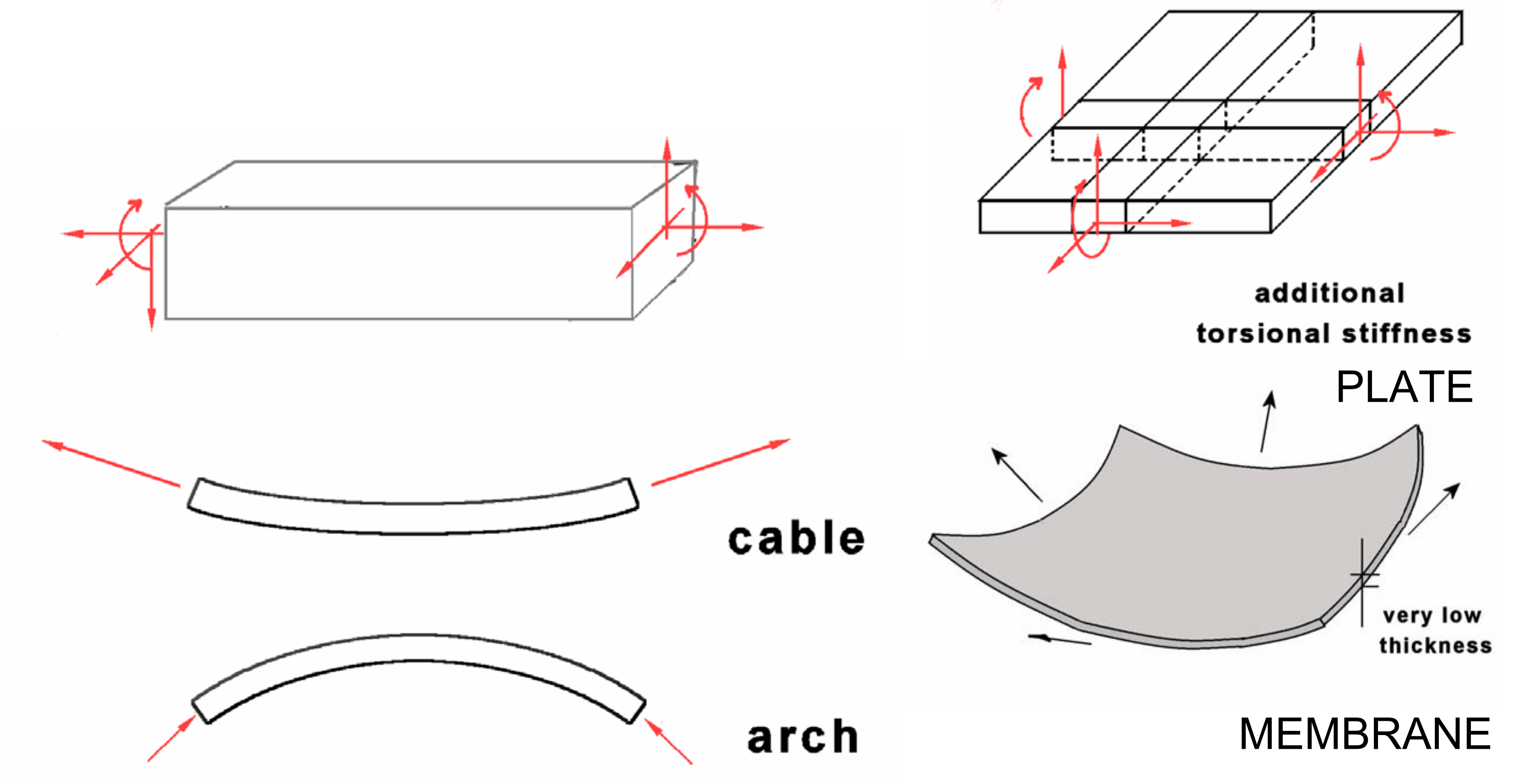
$$M_2 = M_1 + \frac{dM_1}{dx}dx$$

$$\frac{dF_1}{dx} + p = 0$$

$$\frac{dM_1}{dx}dx - F_1 dx - \cancelto{0}{p\frac{dx^2}{2}} = 0$$

$$\frac{d^2M}{dx^2} + p = 0$$

PLATES, SHELLS, MEMBRANES



PLATE

MEMBRANE

(easy to be bent)

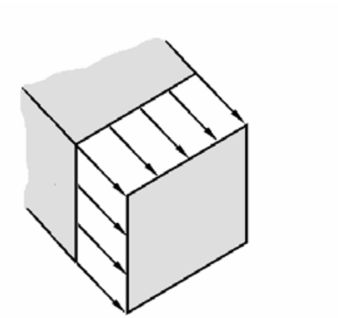
There could be a combination of membrane and plates

THIN WALLED STRUCTURES

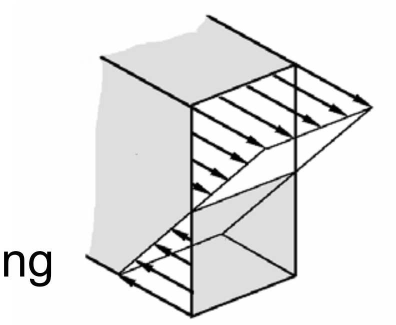
Membrane behavior is always preferred: the material is used in the most effective way.

Closed thin walled sections are preferrably used in aerospace structures

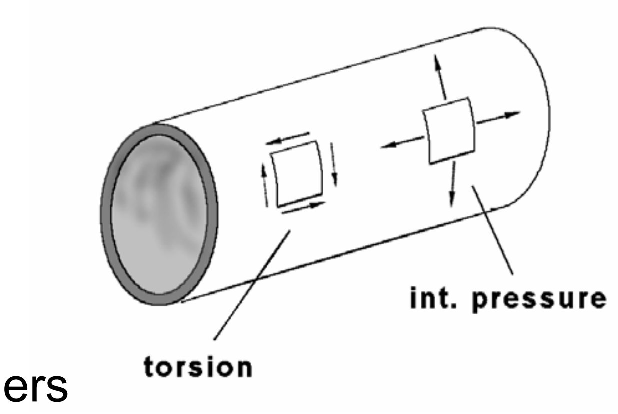
membrane



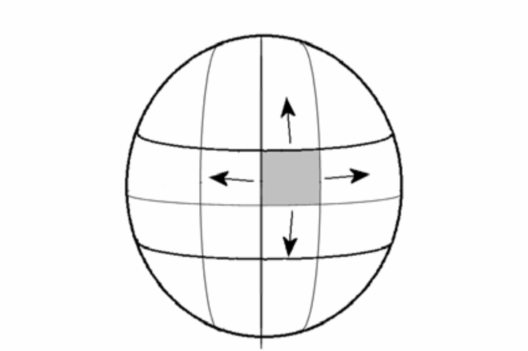
bending



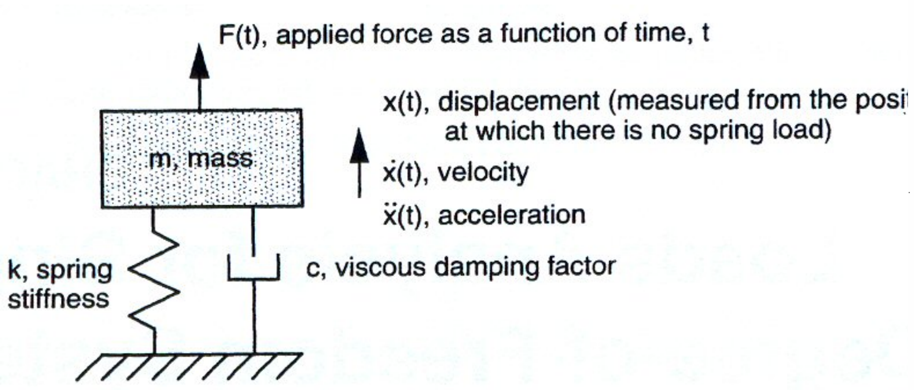
cylinders

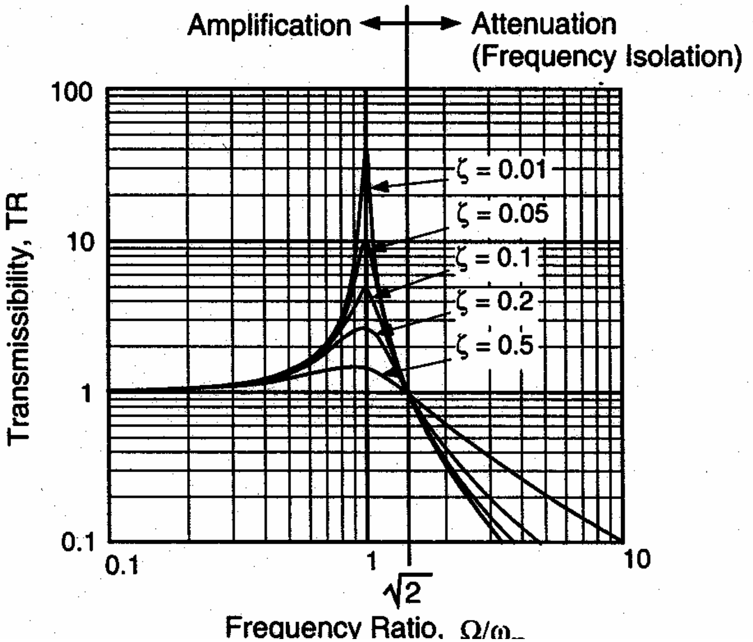


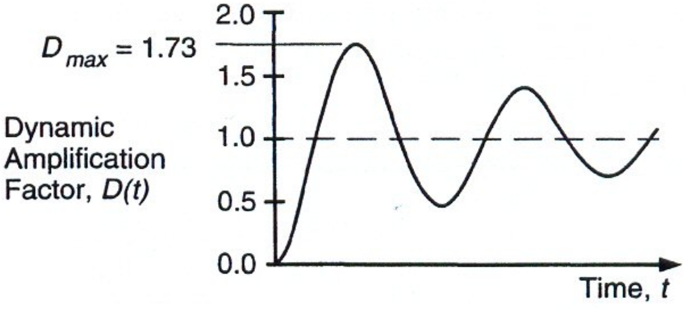
spheres



DYNAMICS: RESONANCE AND DYNAMIC LOAD INCREMENTS







Dynamic Amplification Factor for an SDOF System with a 10% Damping Ratio Under an Instantaneously Applied, Constant Load.

$$D_{max} = \frac{x_{max}}{F_0 / k} = \frac{1}{\sqrt{\left[1-\left(\frac{\Omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\Omega}{\omega_n}\right)^2}}$$

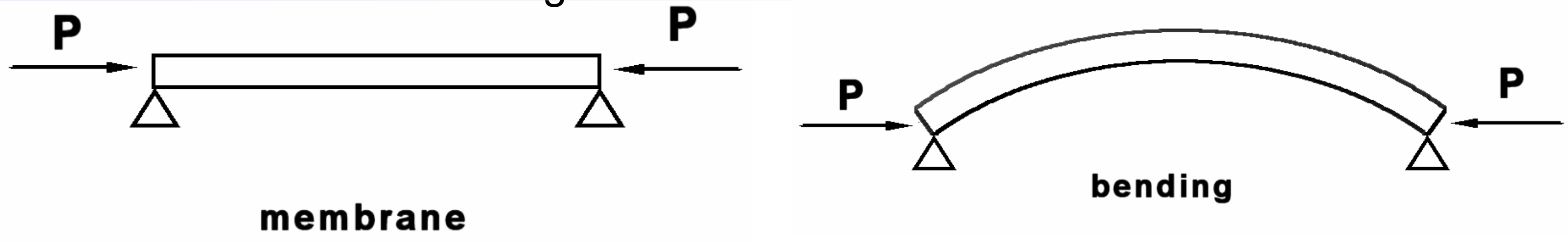
BUCKLING AND STABILITY (1)

In previous examples the equilibrium configuration is the original one. Sometimes the equilibrium could be also reached in a different configuration. Moreover it could happen that in presence of a slightly different geometry of the body or of the applied loads the equilibrium is not maintained.

The sensitivity of the capability of mantaining an equilibrium configuration is studied by the theory of stability.

The most famous example of unstable equilibrium is the buckling of a beam under compression, studied by Euler.

By subjecting the beam at increasing P, for a certain critical value of P (Eulerian buckling load) the original equilibrium configuration becomes unstable and equilibrium is reached in a deformed configuration.



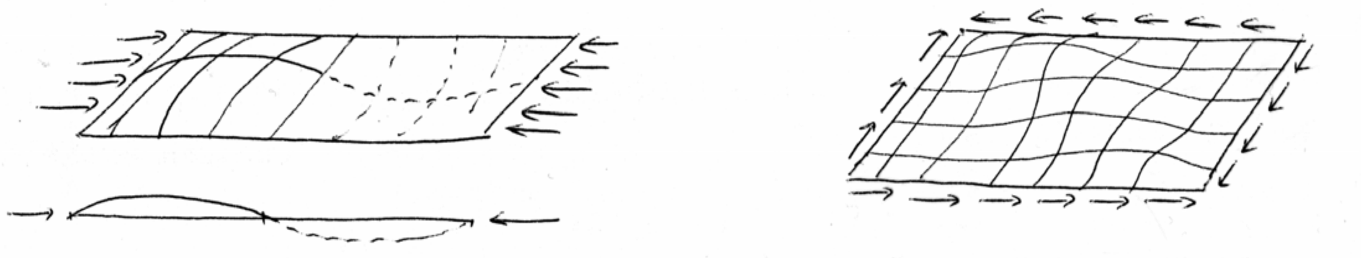
BUCKLING AND STABILITY (2)

The buckling loads depends upon the geometry of the section (I) the material (E), the overall geometry (L) of the structure and the boundary conditions. For simply supported beams:

$$P_{Eul} = \frac{\pi^2 EJ}{\ell^2}$$

J : *minimum moment of inertia*

Plates under compression or shear could have stability problems



Buckling has consequences both on STIFFNESS (a flexible structure has strong displacements) and on STRENGTH.

In fact, especially in bending behavior, the failure of the material (yielding or ultimate load) can be reached in the deformed configuration of equilibrium or, even worse, in absence of equilibrium.

CONCLUDING REMARKS

Function of the structural system: materialisation of geometry and support, stiffness, strength, low density

Material behaviour – main failure modes

Structural behaviour

Stress analysis, Dynamics, Stability, Thermoelasticity