COMPOSITE MATERIALS DESIGN

1. Basic Concepts

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A composite is a new material formed by the combination of two or more distinct materials to form other material with enhanced properties

Examples:

natural composites

- wood consists of cellulose fibers in a lignin matrix
- bone consists as fiberlike osteons embedded in an interstitial bone matrix

Modern manmade composites

- fiberglass boats are made of a UP reinforced with glass fibers
- hibrid composites- epoxy resin with kevlar and carbon fiber

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What’s a composite material

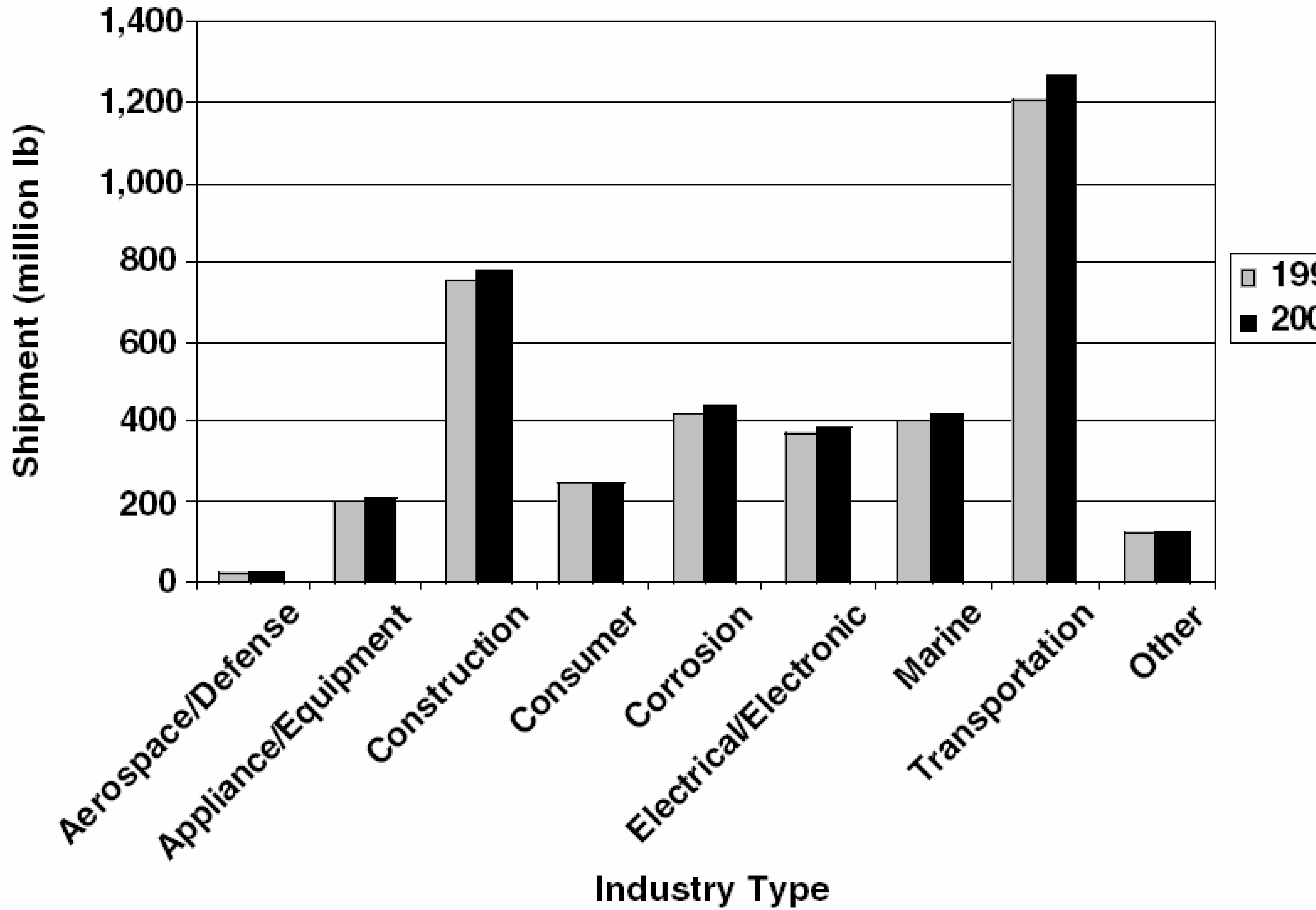
Composites are formed by the combination of two or more components to achieve properties : mechanical, chemical, electrical, that are superior to those of the constituents.

- fibres: provide most of the stiffness and strenght
- matrix: binds the fibers together providing load transfer between them and between the composite and the external loads and supports
- design remarks: Unlike conventional materials the properties of the composites can be designed simultaneously with the structural aspects. Composite properties can be varied continously over a broad range of values, under the control of the designer.
- Micromechanics: predict very well some mechanical properties of composites, using the combination of fibers and matrix properties

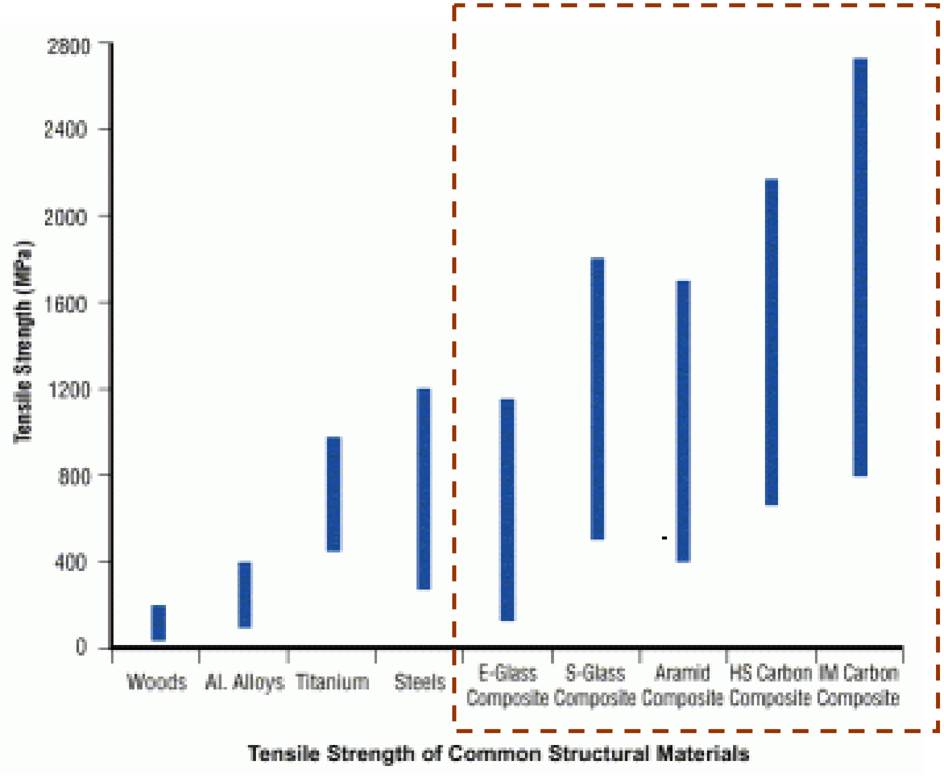
Basic Concepts

Composites make up a very broad and important class of engineering materials. World annual production is over 12 million tonnes and the market has in recent years growing at 8-12% per annum. Composites are used in a wide variety of applications. Furthermore, there is considerable scope for tailoring their structure to suit the service conditions This concept is well illustrated by biological materials *such as wood,* *bone, teeth and hide; these are all composites with complex internal structures designed to given mechanical properties well suited to performance requirements. Adaptation of manufactured composite structures for different engineering purpouse requieres input from several branches of science.*

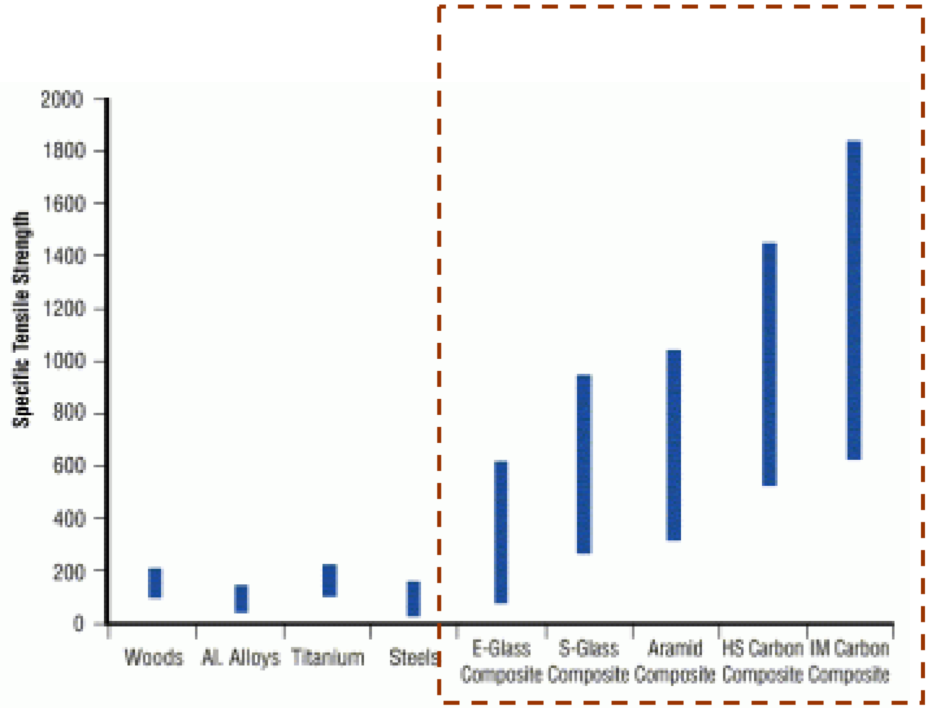
U.S. Composites Market Breakdown



For its excellent Tensile Strenght



SPECIFIC TENSILE STRENGHT



Specific Tensile Strength of Common Structural Materials

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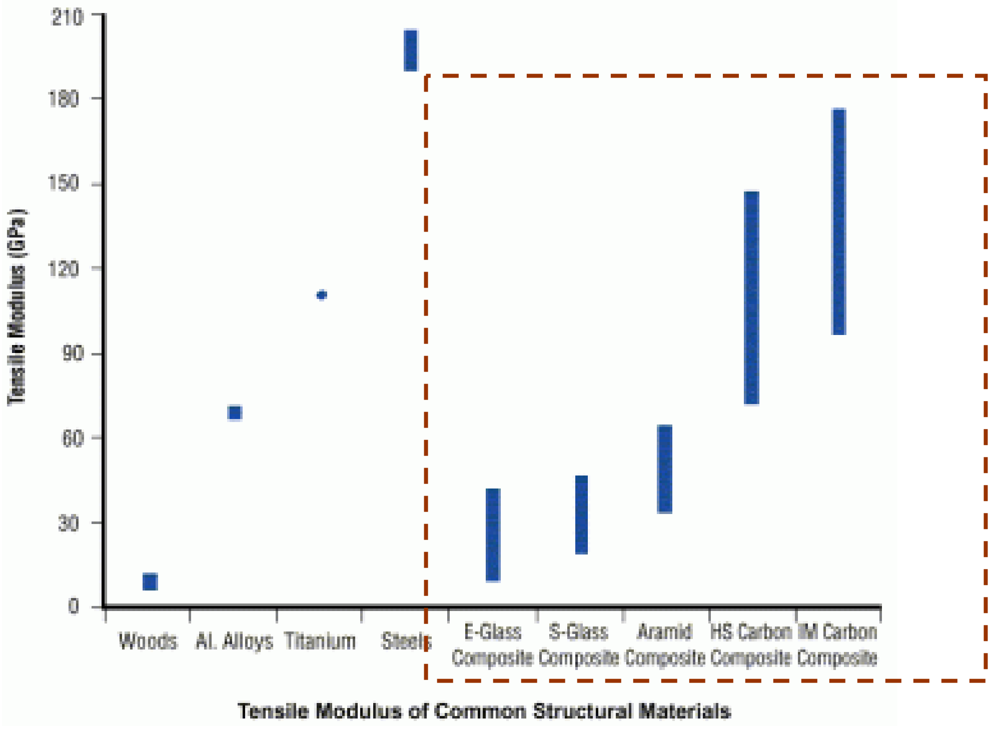
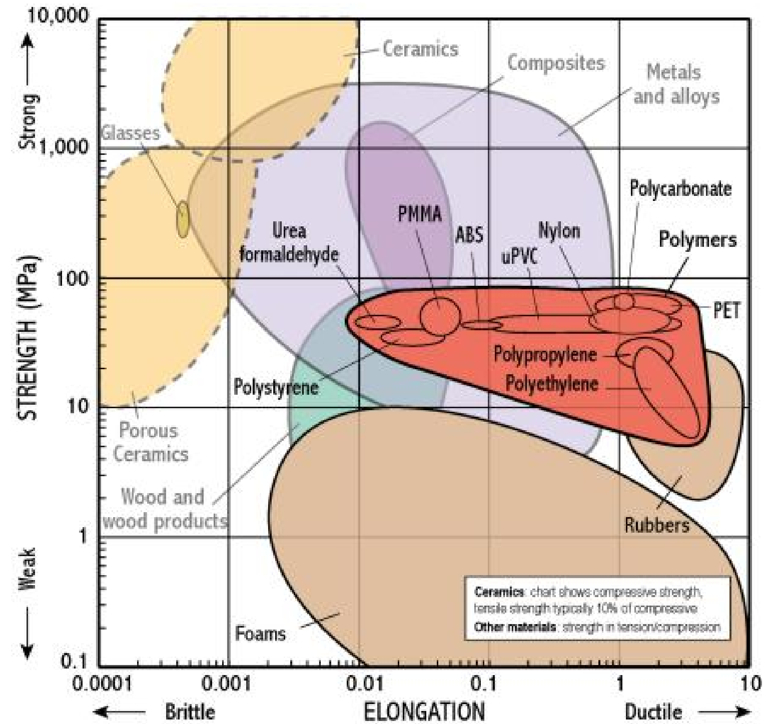
TENSILE MODULUS

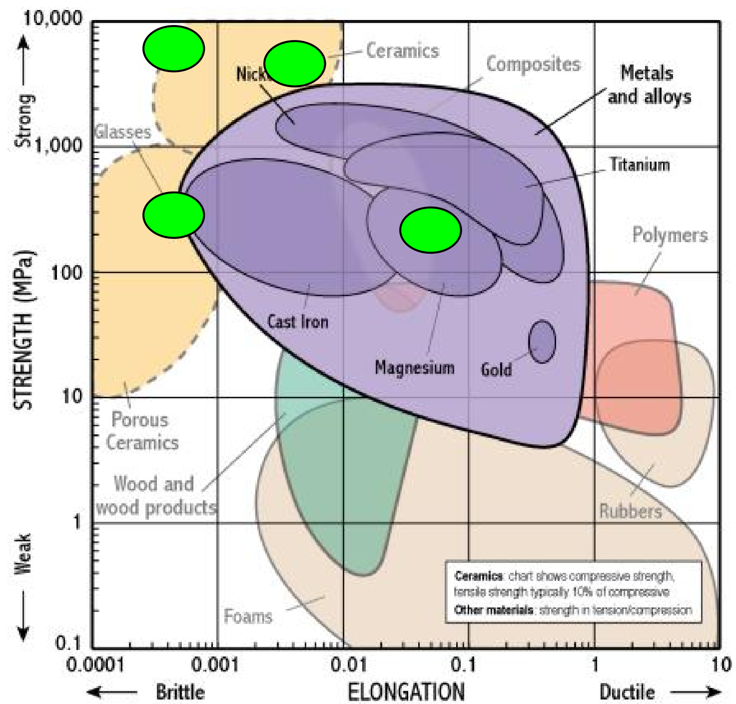


Resin systems such as epoxies and polyesters have limited use for the manufacture of structures on their own, since their mechanical properties are not very high when compared to, for example, most metals. However, they have desirable properties, most notably their ability to be easily formed into complex shapes.



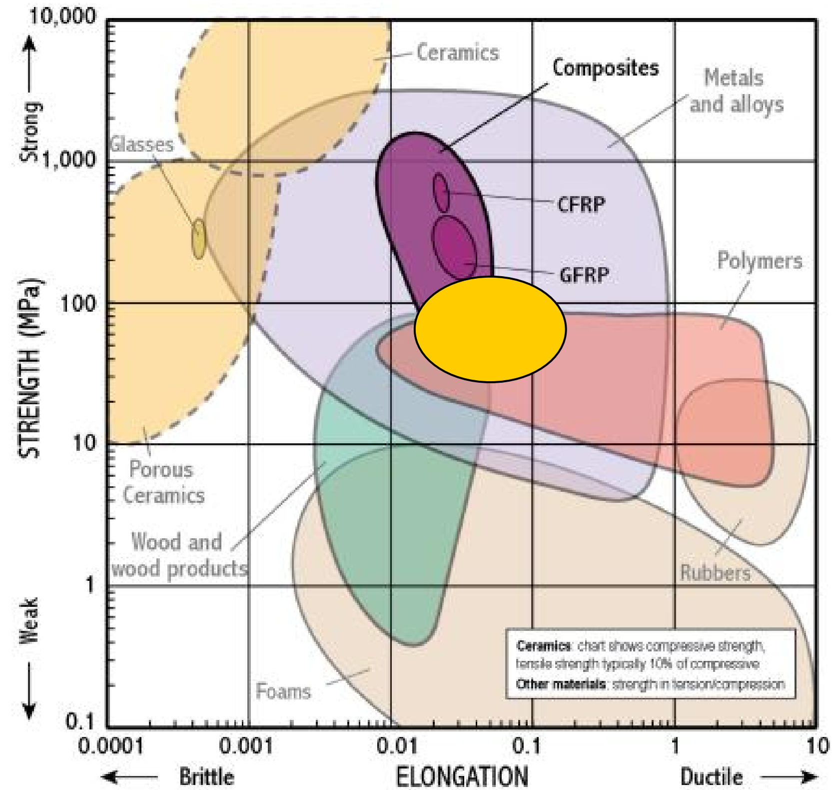
Basic Concepts

Materials such as glass, aramid, carbon and boron have extremely high tensile and compressive strength but in 'solid form' these properties are not readily apparent. This is due to the fact that when stressed, random surface flaws will cause each material to crack and fail well below its theoretical 'breaking point'. To overcome this problem, the material is produced in fibre form, so that, although the same number of random flaws will occur, they will be restricted to a small number of fibres with the remainder exhibiting the material's theoretical strength. Therefore a bundle of fibres will reflect more accurately the optimum performance of the material. However, fibres alone can only exhibit tensile properties along the fibre's length, in the same way as fibres in a rope.

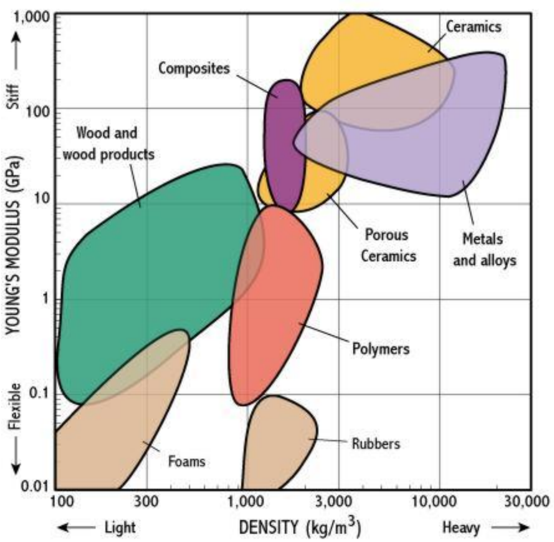


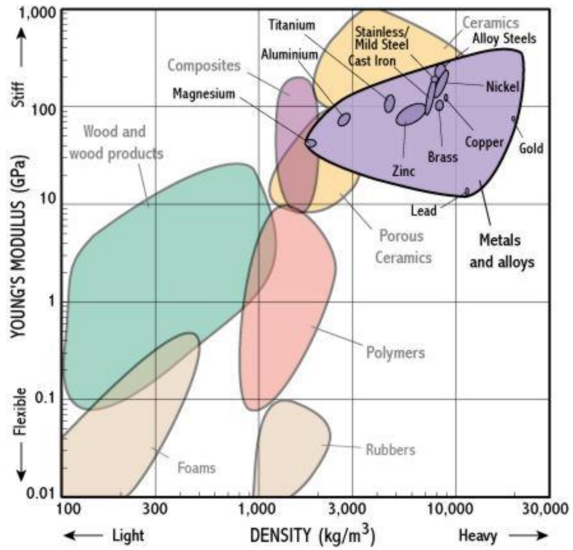
Basic Concepts

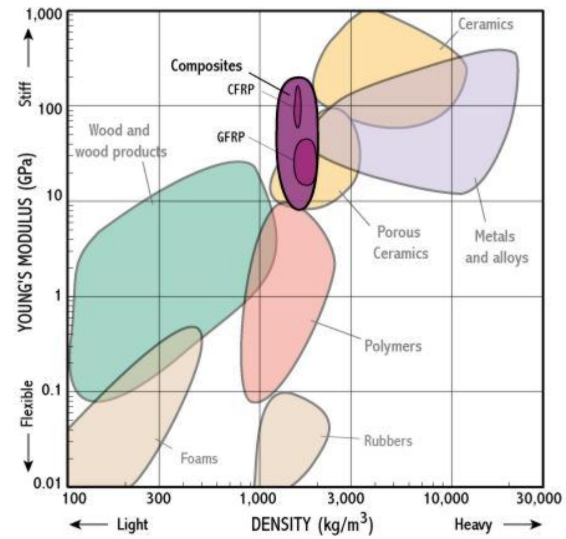
It is when the resin systems are combined with reinforcing fibres such as glass, carbon and aramid, that exceptional properties can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and also protects the fibres from damage caused by abrasion and impact. High strengths and stiffnesses, ease of moulding complex shapes, high environmental resistance all coupled with low densities, make the resultant composite superior to metals for many applications.



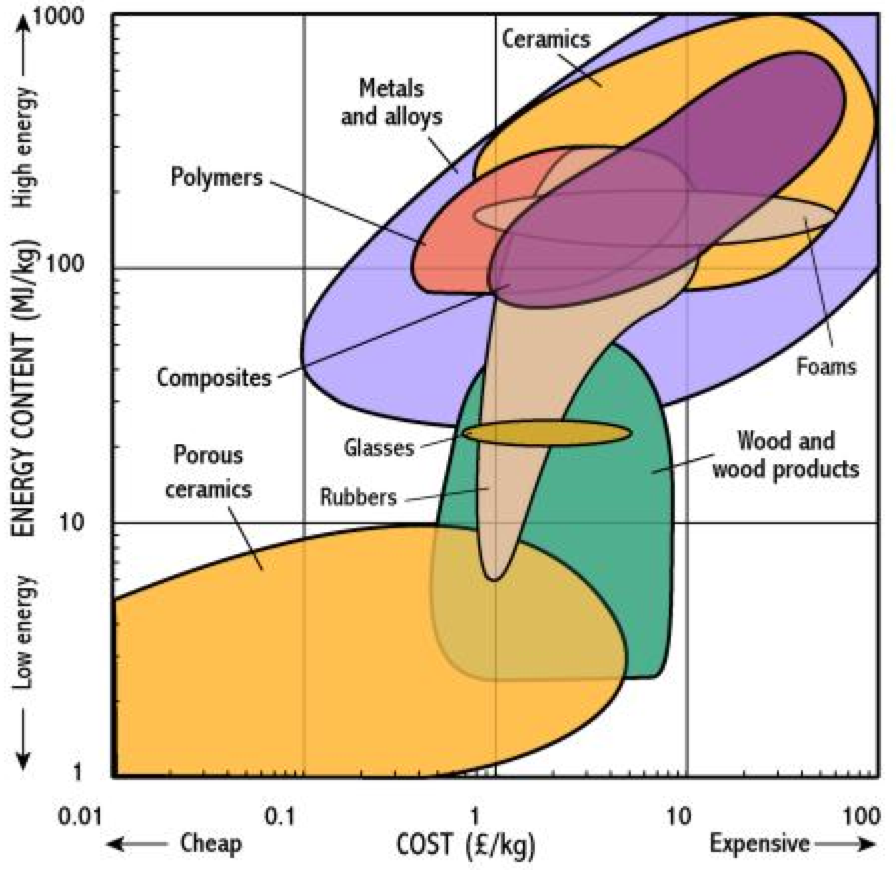
TENSILE MODULUS versus DENSITY







ENERGY CONTENT versus COST



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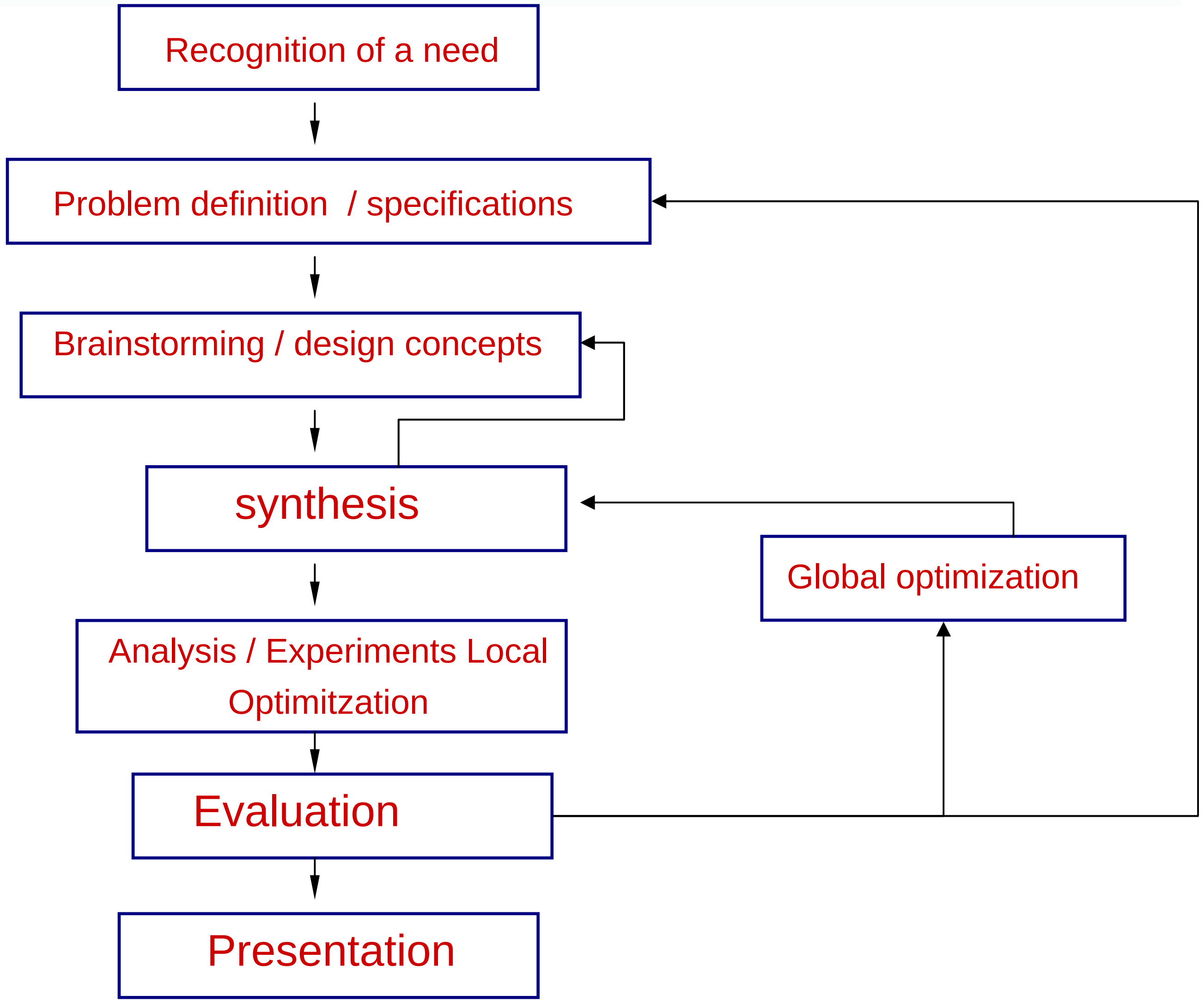
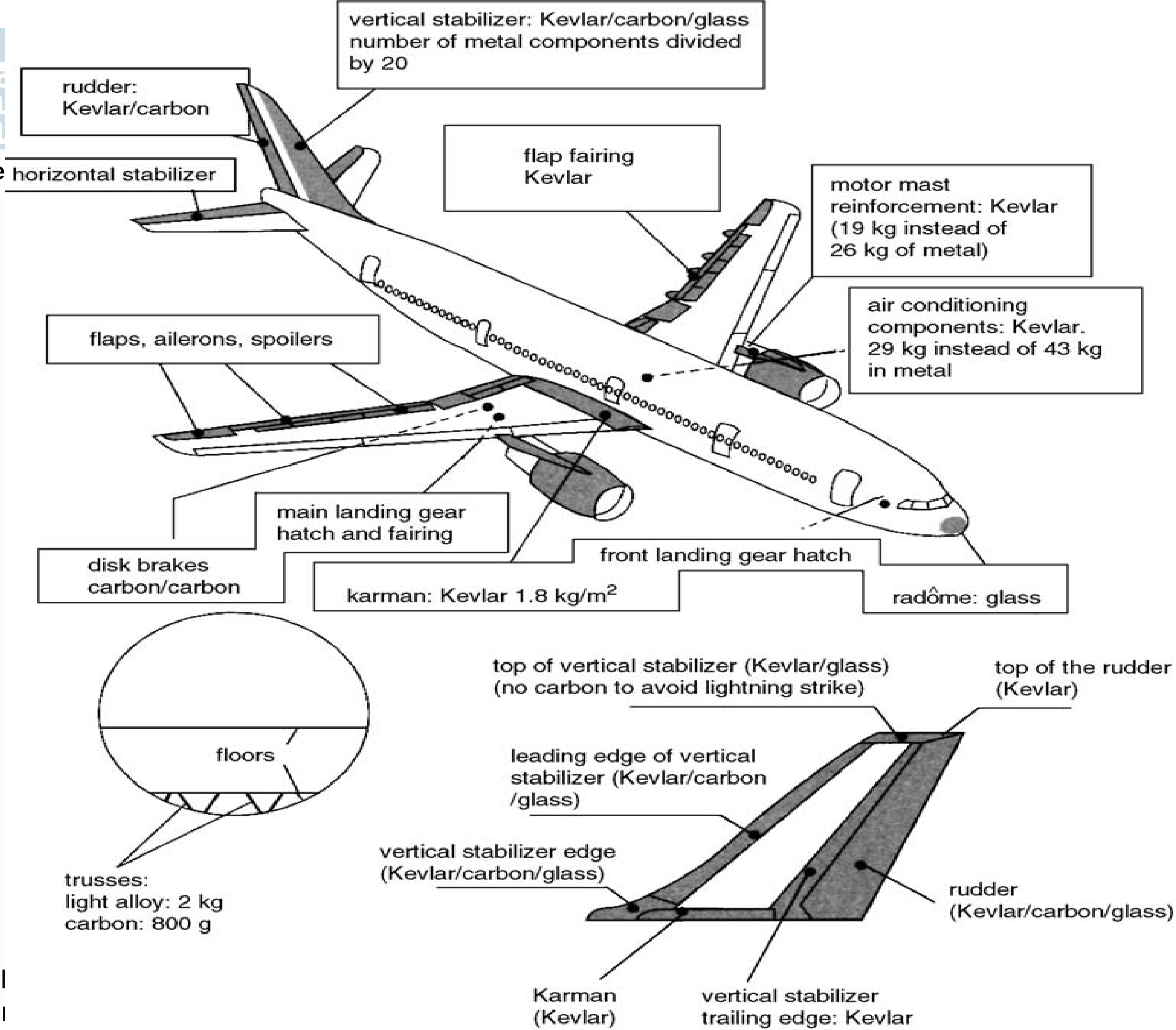
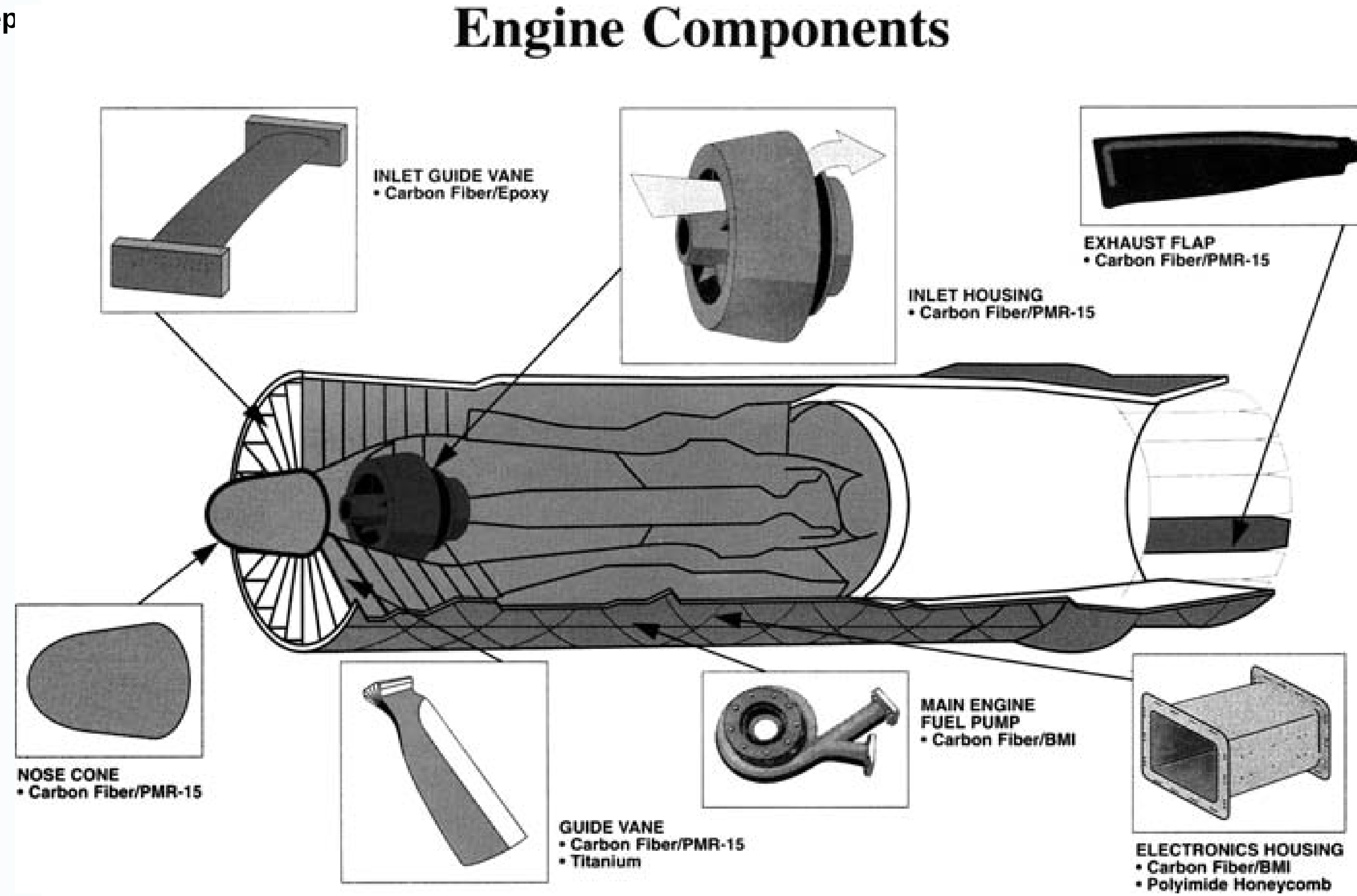
How design a composite material?

Basic Concepts



Recognition of a need design begins by recognizing a need. Satisfying this need becomes the problem of the designer

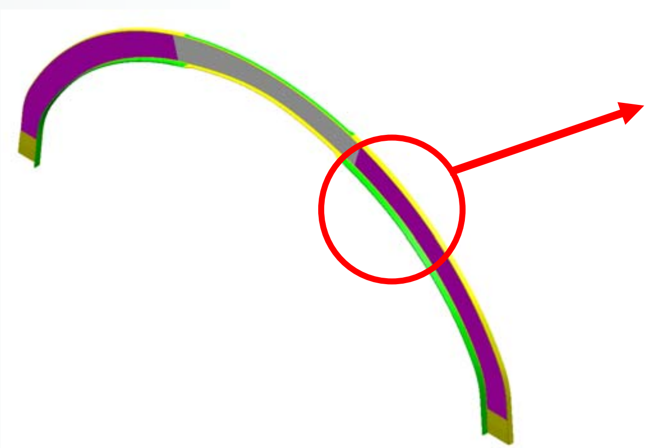

vertical stabilizer: Kevlar/carbon/glass number of metal components divided by 20
rudder: Kevlar/carbon
horizontal stabilizer
flap fairing Kevlar
motor mast reinforcement: Kevlar (19 kg instead of 26 kg of metal)
air conditioning components: Kevlar. 29 kg instead of 43 kg in metal
flaps, ailerons, spoilers
main landing gear hatch and fairing
disk brakes carbon/carbon
front landing gear hatch
karman: Kevlar 1.8 kg/m2
radôme: glass
floors
trusses: light alloy: 2 kg carbon: 800 g
top of vertical stabilizer (Kevlar/glass) (no carbon to avoid lightning strike)
top of the rudder (Kevlar)
leading edge of vertical stabilizer (Kevlar/carbon /glass)
vertical stabilizer edge (Kevlar/carbon/glass)
rudder (Kevlar/carbon/glass)
Karman (Kevlar)
vertical stabilizer trailing edge: Kevlar

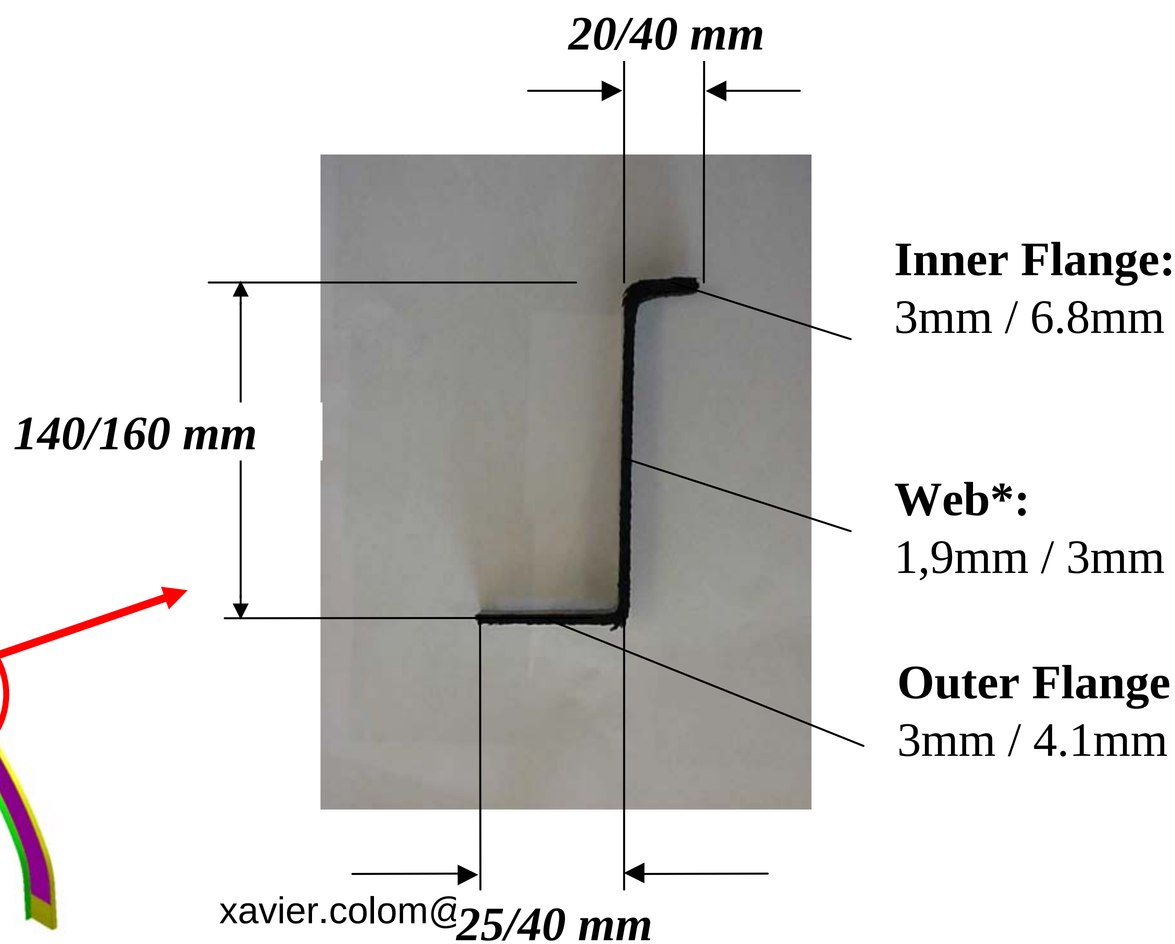

Engine Components
INLET GUIDE VANE
• Carbon Fiber/Epoxy
EXHAUST FLAP
• Carbon Fiber/PMR-15
INLET HOUSING
• Carbon Fiber/PMR-15
NOSE CONE
• Carbon Fiber/PMR-15
GUIDE VANE
• Carbon Fiber/PMR-15
• Titanium
MAIN ENGINE
FUEL PUMP
• Carbon Fiber/BMI
ELECTRONICS HOUSING
• Carbon Fiber/BMI
• Polyimide Honeycomb

How design a composite material?

Problem definition / specifications The designers, with the concurrence of the user and other parties involved (marketing, etc..) defines the problem in engineering as well as in layman's term, so that every one involved understands the problem.

Section frame





How design a composite material?

Basic Concepts

Brainstorming / design concepts

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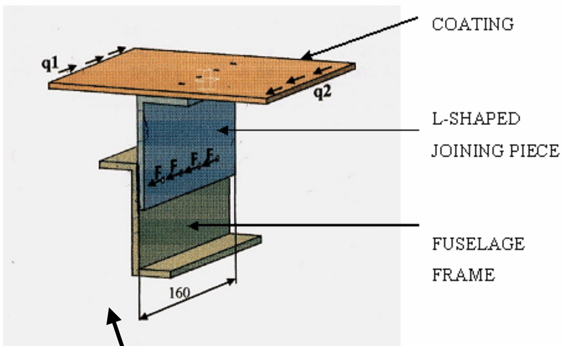
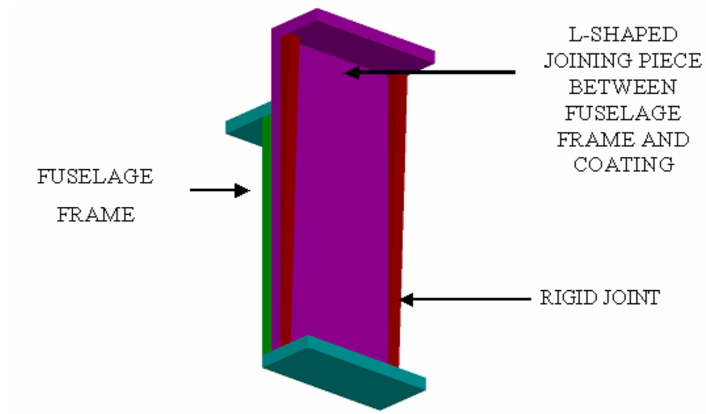
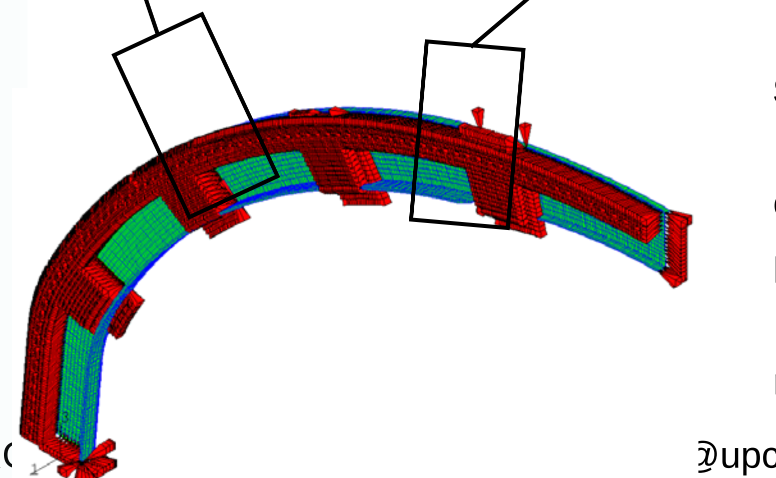
synthesis

Syntesis is the selection of the optimum solution among the many combinations proposed. Synthesis, and design relies on analysis to predict the behaviour of the product before one is actually fabricated







Simple Joining L-shaped Piece:

•X displacements are constrained on nodes corresponding to the contact surface.

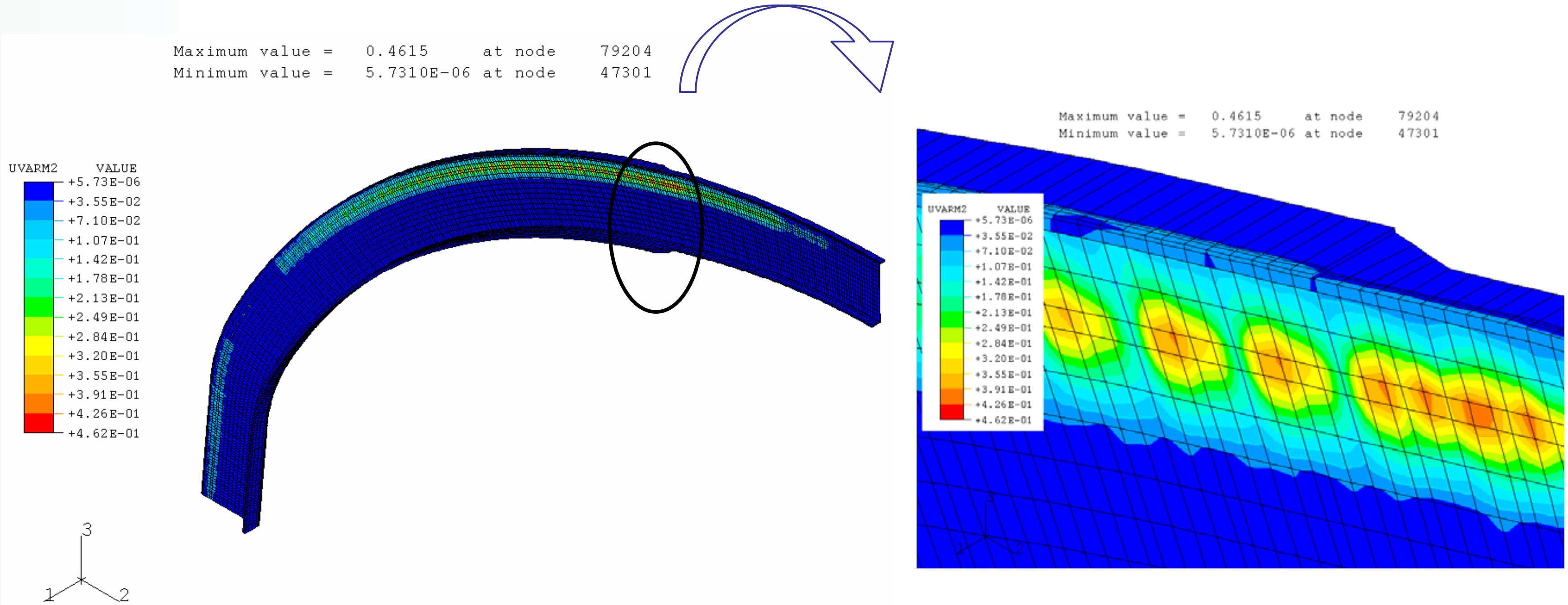
Rigid Joining L-shaped Piece:

•X,Y and Z displacements constrained on nodes corresponding to the contact surface.

How design a composite material?

Analysis / Experiments Local Optimitzation

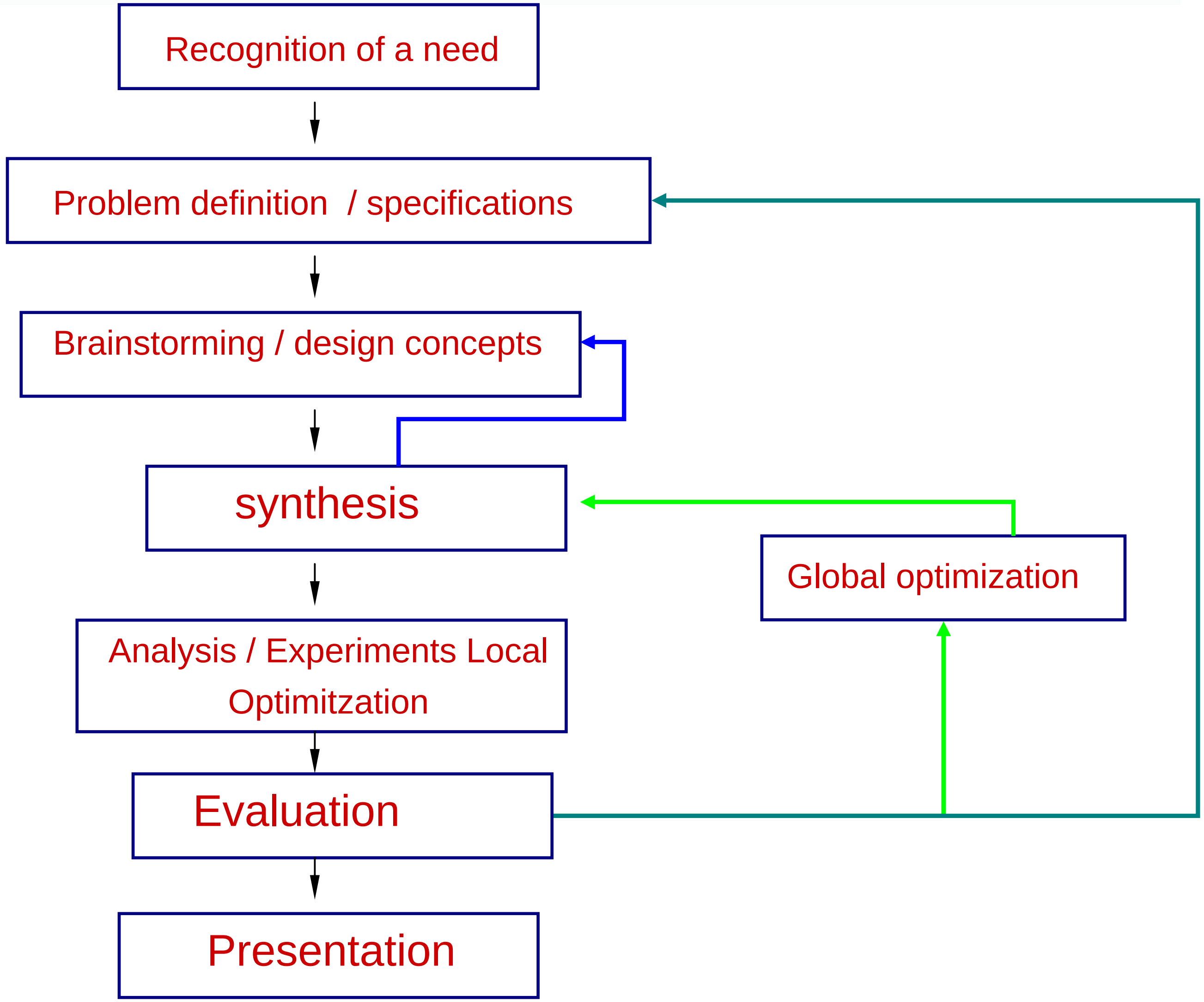
Analysis uses mathematical models to construct an abstract representation of the reality from which the designer can extract information about the likely behaviour of the real product. The optimized solution is then evaluated against the performance criteria set forth in the definition of the problem



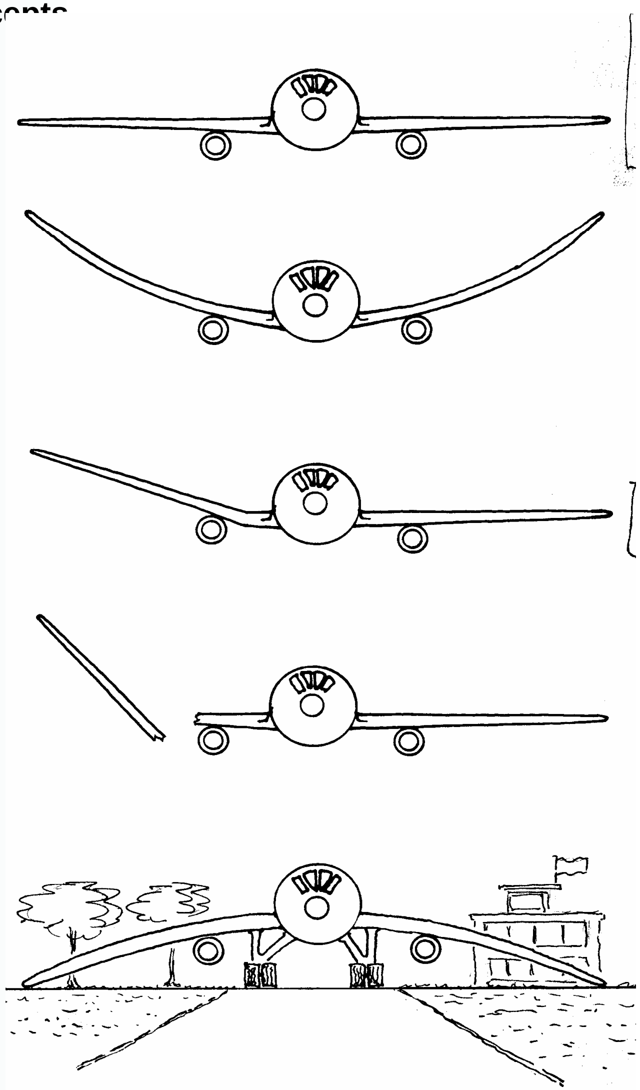
An iterative process takes place as depicted in previuos/next organigram

How design a composite material?

Basic Concepts



Evaluation of Mechanical properties



Stiff
Strong
Tough
Light

Not stiff enough (need bigger E)

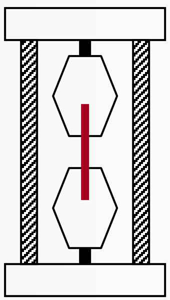
Not strong enough (need bigger σy)

Not tough enough (need bigger Kic)

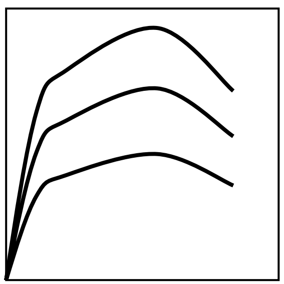
Too heavy (need lower ρ)

What do we need to know about materials to design a product?

Data capture → *Statistical analysis* → *Selection of material and process* → *Economic analysis and business case*



Test

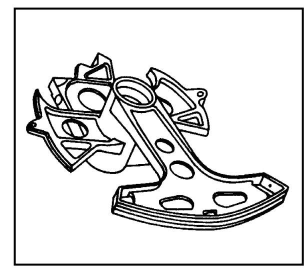


Test data

Mechanical Properties

Bulk Modulus	4.1 -	4.6 GPa
Compressive Strength	55 -	60 MPa
Ductility	0.06 -	0.07
Elastic Limit	40 -	45 MPa
Endurance Limit	24 -	27 MPa
Fracture Toughness	2.3 -	2.6 $MPa.m^{1/2}$
Hardness	100 -	140 MPa
Loss Coefficient	0.009-	0.026
Modulus of Rupture	50 -	55 MPa
Poisson's Ratio	0.38 -	0.42
Shear Modulus	0.85 -	0.95 GPa
Tensile Strength	45 -	48 MPa
Young's Modulus	2.5 -	2.8 GPa

Design data



Potential applications

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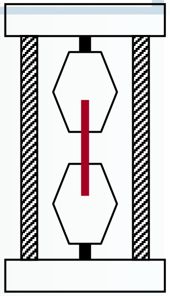
Successful applications

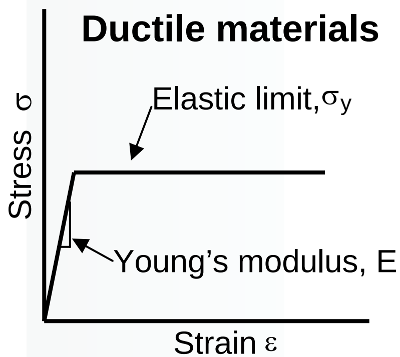
Characterisation (Test, Test data, Design data)

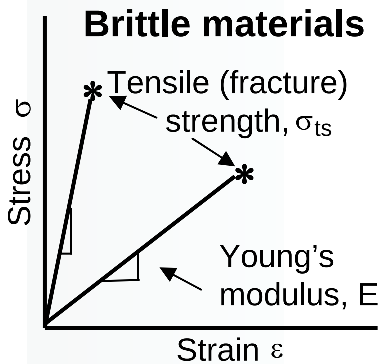
Selection and implementation (Potential applications, Successful applications)

How design a composite material?

Mechanical properties







General

Weight: Density ρ, Mg/m^3

Expense: Cost/kg C_m, \$/kg

Mechanical

Stiffness: Young's modulus E, GPa

Strength: Elastic limit σ_y, MPa

Fracture strength: Tensile strength σ_{ts}, MPa

Brittleness: Fracture toughness K_{ic}, $MPa.m^{1/2}$

Thermal

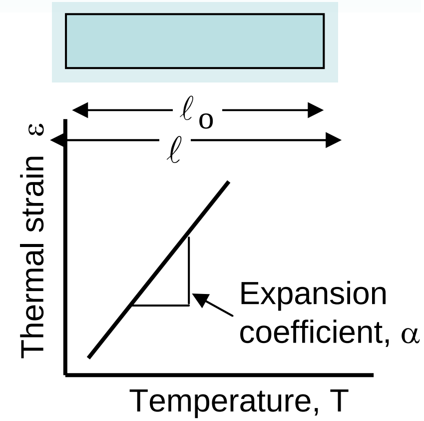
Expansion: Expansion coeff. α, 1/K

Conduction: Thermal conductivity λ, W/m.K

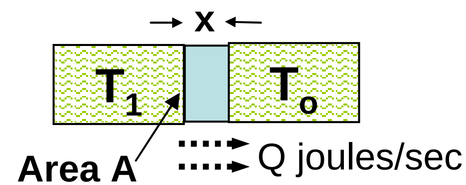
Electrical

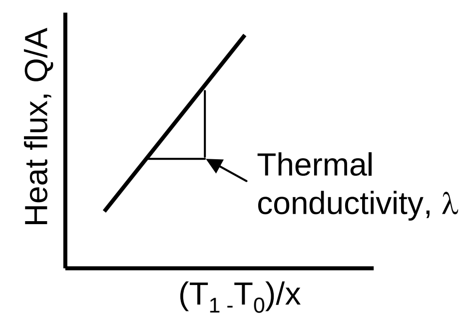
Conductor? Insulator?

Thermal expansion



Thermal conduction



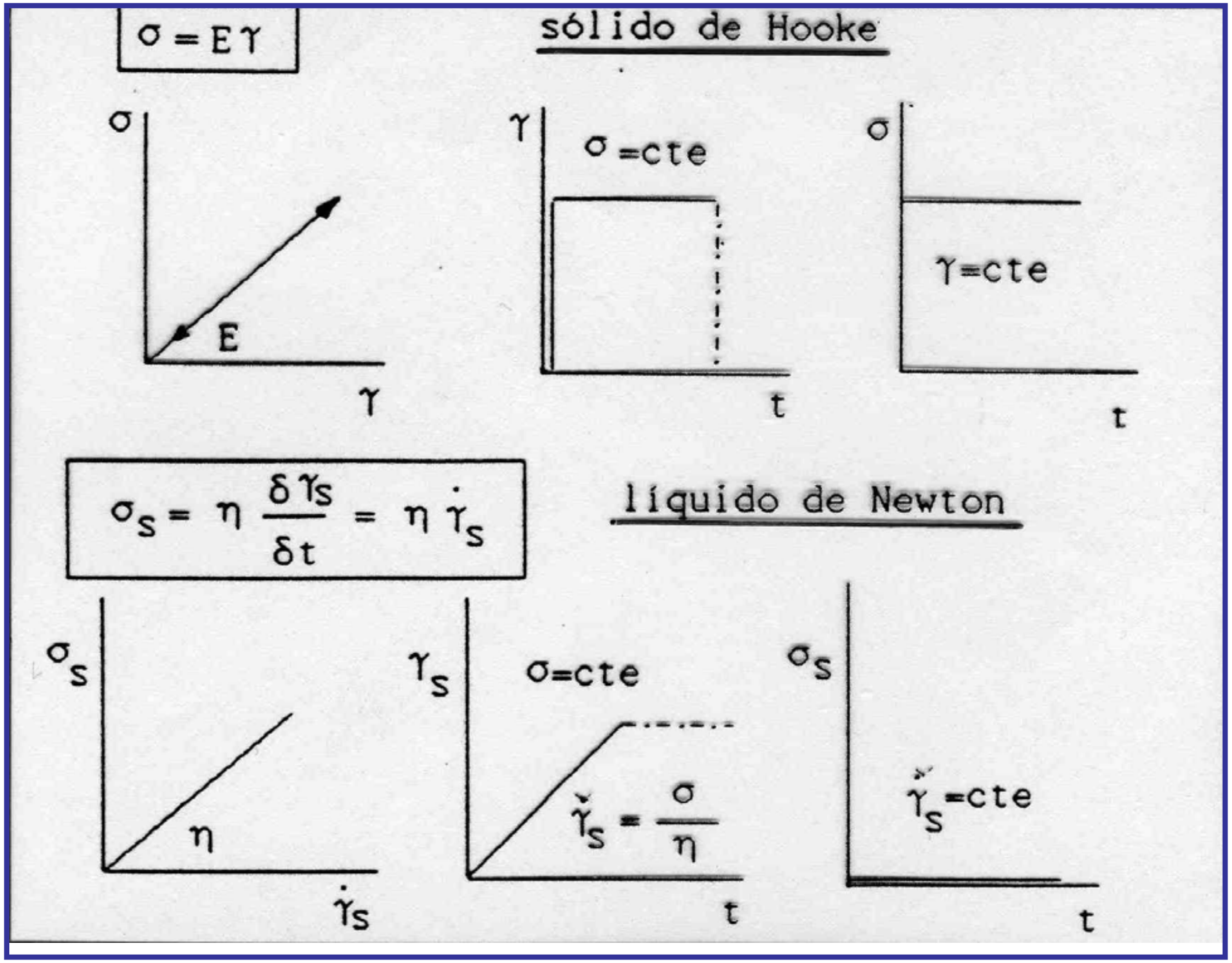


523 125% Buscar

Table 1.1 Properties of Commonly Used Resins

Application	*Price of Previous Construction*	*Price of Composite Construction*
65 m^3 reservoir for chemicals	Stainless steel + installation: 1.	0.53
Smoke stack for chemical plant	Steel: 1.	0.51
Nitric acid vapor washer	Stainless steel: 1.	0.33
Helicopter stabilizer	Light alloys + steel (16 kg): 1.	Carbon/epoxy (9 kg): 0.45
Helicopter winch support	Welded steel (16 kg): 1.	Carbon/epoxy (11 kg): 1.2
Helicopter motor hub	(Mass: 1): 1.	Carbon/Kevlar/epoxy (mass: 0.8): 0.4
X–Y table for fabrication of integrated circuits	Cast aluminum: Rate of fabrication: 30 plates/hr	Carbon/epoxy honeycomb sandwich: 55 plates/hr
Drum for drawing table	Speed of drawing: 15 to 30 cm/sec	Kevlar/epoxy: 40 to 80 cm/sec
Head of welding robot	Aluminum: Mass = 6 kg	Carbon/epoxy: Mass = 3 kg
Weaving machine rod	Aluminum: Rate = 250 shots/minute	Carbon/epoxy: Rate = 350 shots/minute
Aircraft floor	(Mass = 1): 1.	Carbon/Kevlar/epoxy (mass: 0.8): 1.7

Viscous plastic behavior



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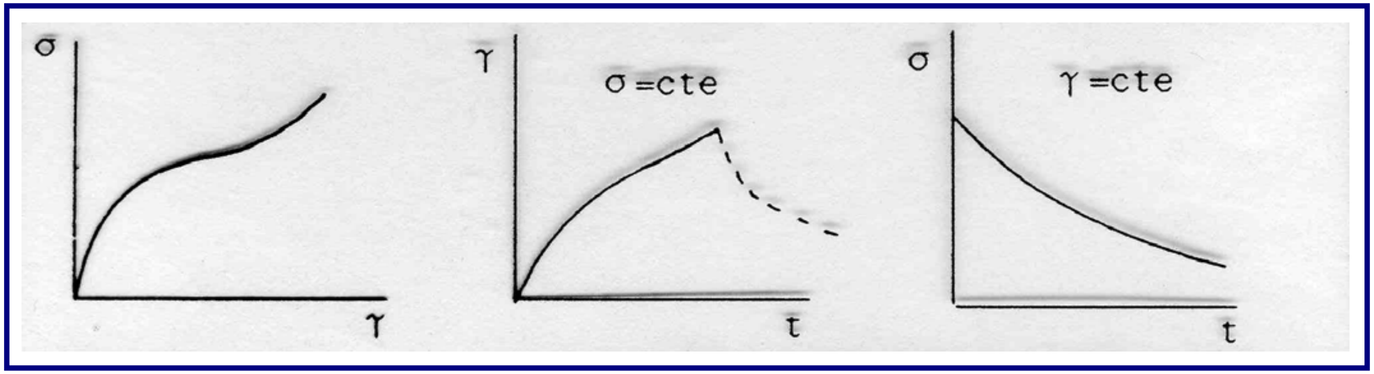
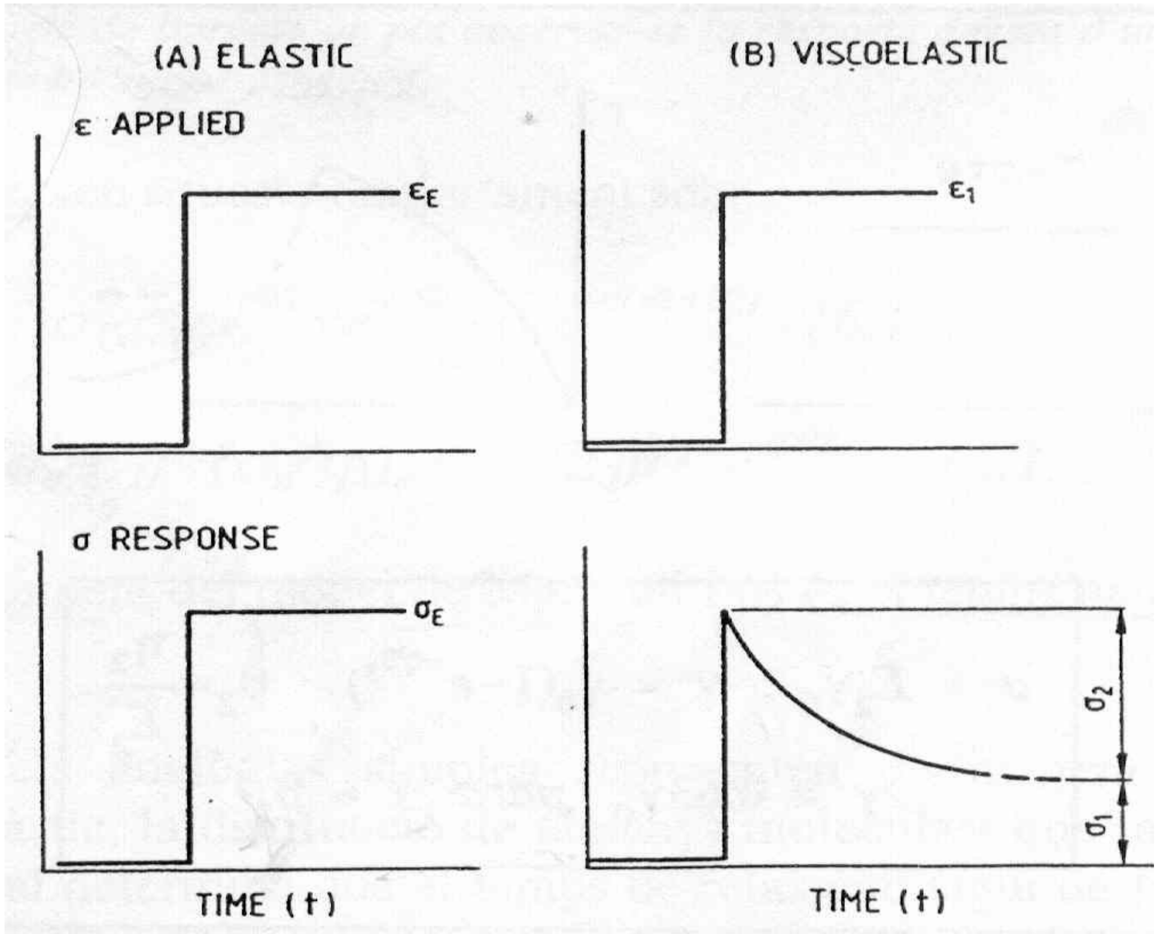
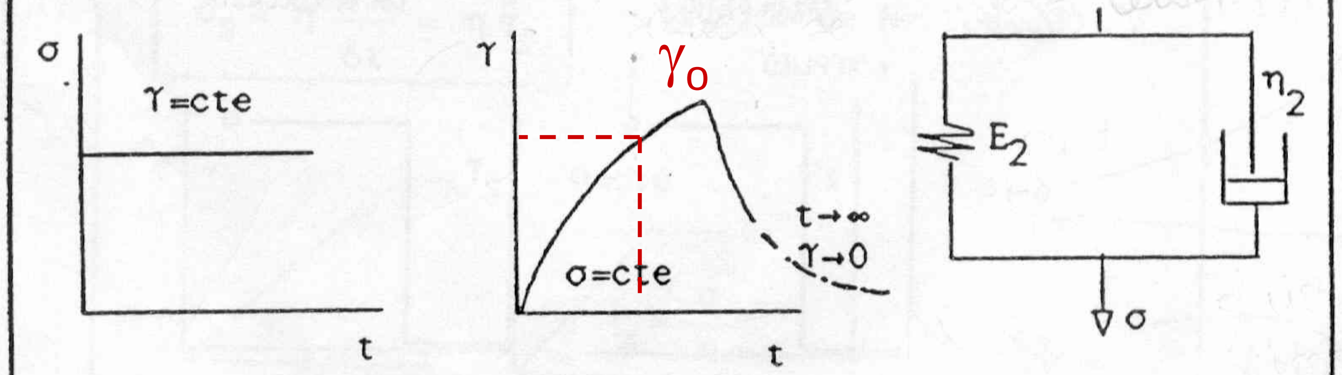

σ
γ
γ
σ =cte
t
σ
γ =cte
t

Maxwell Model (Stress Relaxation)



$\sigma=\sigma o e\text{-}t/\theta 1$ $\theta 1=\eta 1/E1$ $\gamma=(\sigma o/E1)+(\sigma o/\eta 1)t$ $\sigma=0.37\sigma o$ ***per*** $t=\theta 1$

Kelvin-Voigt Model or Creep Deformation (Slow fluency)

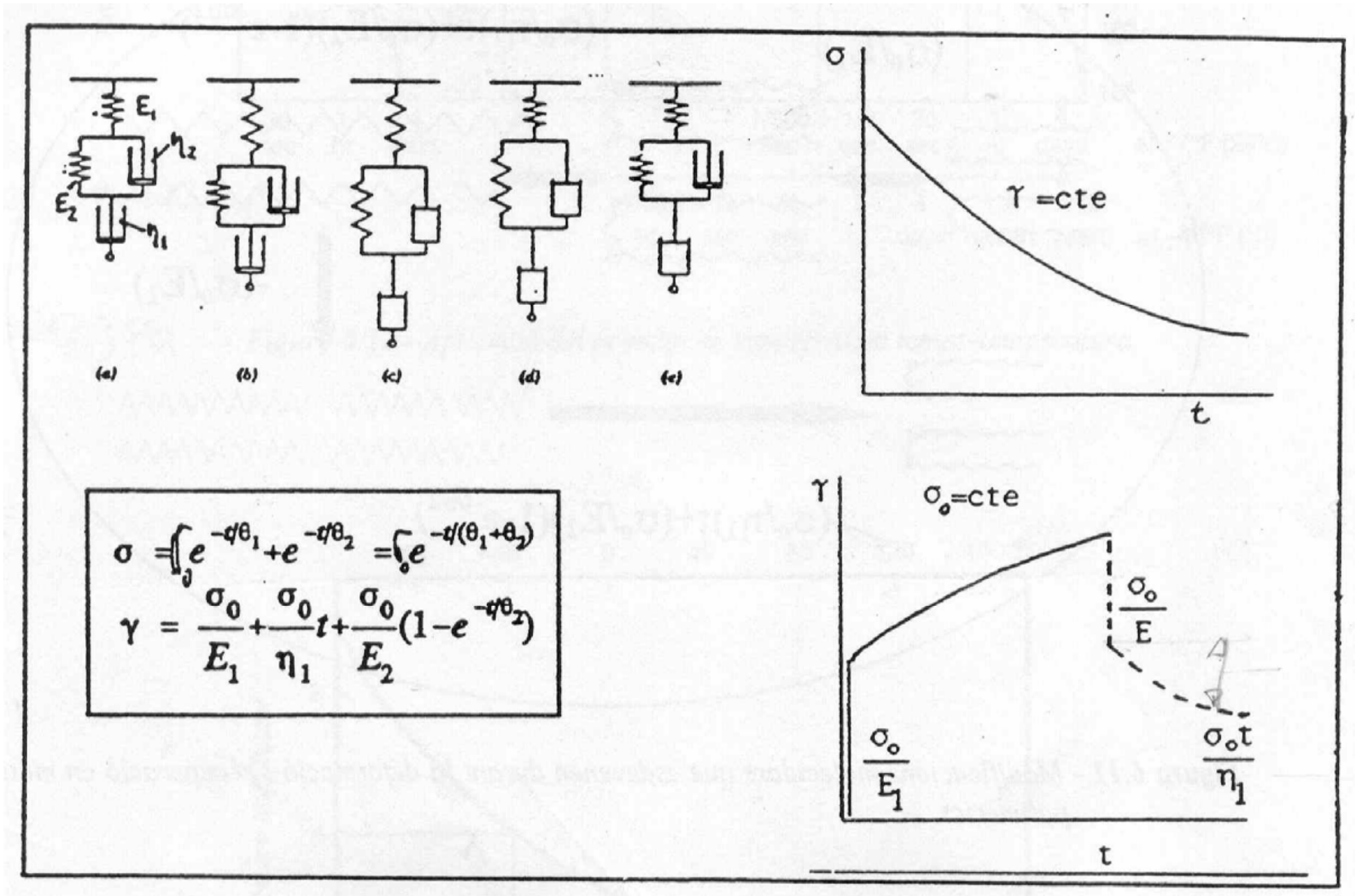


$$\sigma = E_2\gamma_0 \qquad \gamma = \gamma_0(1-e^{-t/\theta_2}) \qquad \theta_2 = \frac{\eta_2}{E_2}$$

$$\gamma = 0.63\gamma_0 \quad para \quad t = \theta_2$$

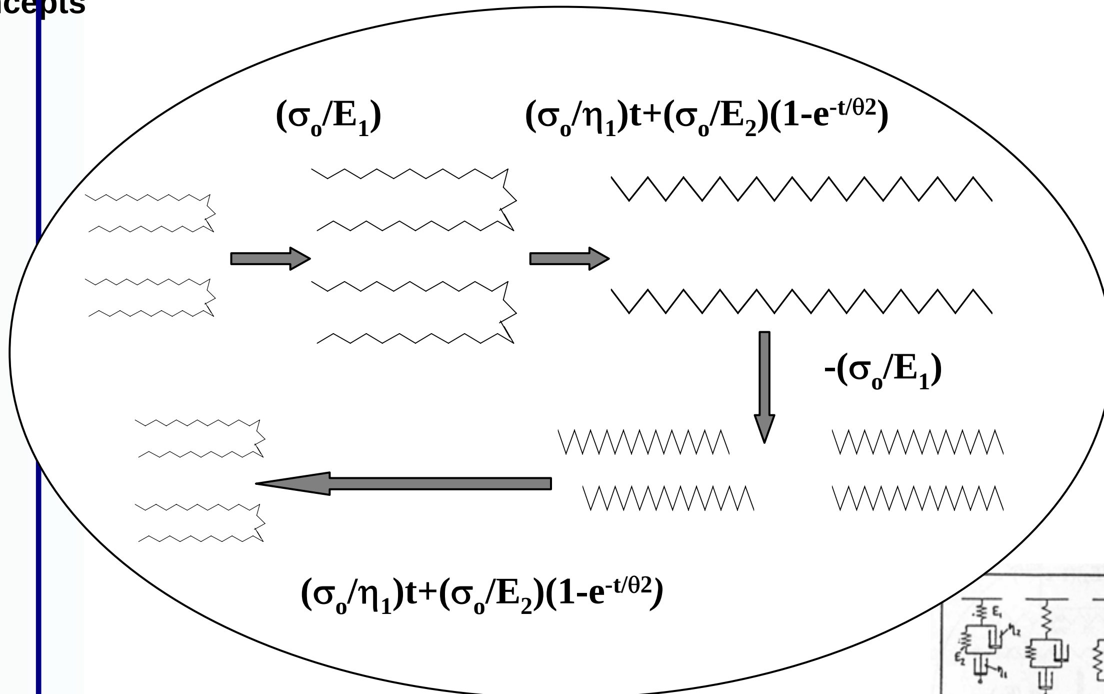
Burgers Model

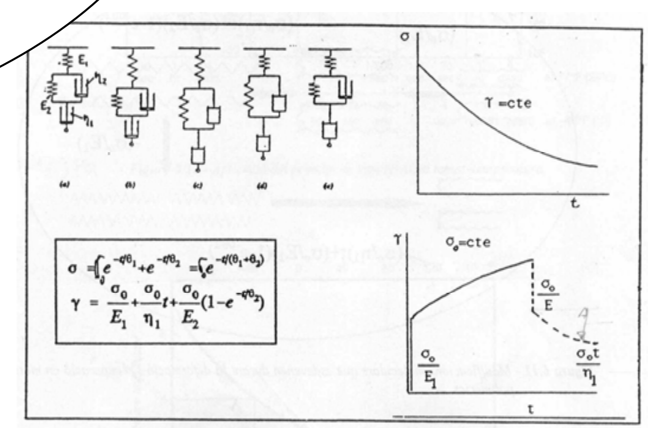
Basic Concepts



Burgers Model

Basic Concepts





Basic Concepts

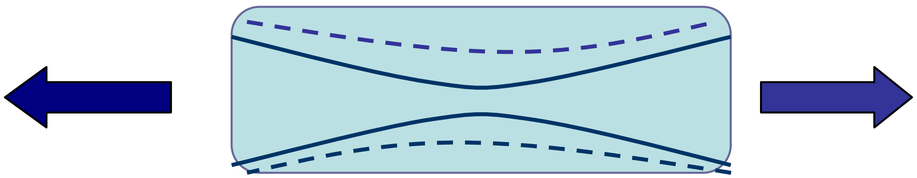
The concept of load transfer

To understand the mechanical behavior of composite we need to know the concept of load sharing between the matrix and the reinforcing phase

There are four main direct loads that any material in a structure has to withstand: tension, compression, shear and flexure.

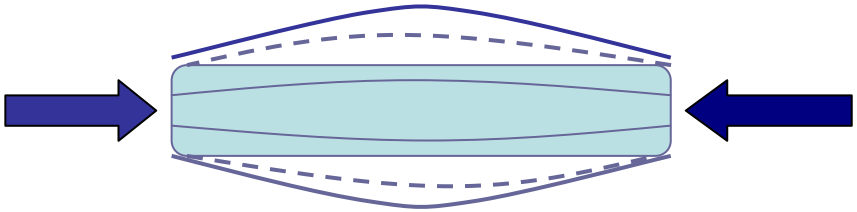
Tension

The figure below shows a tensile load applied to a composite. The response of a composite to tensile loads is very dependent on the tensile stiffness and strength properties of the reinforcement fibers, since these are far higher than the resin system on its own.

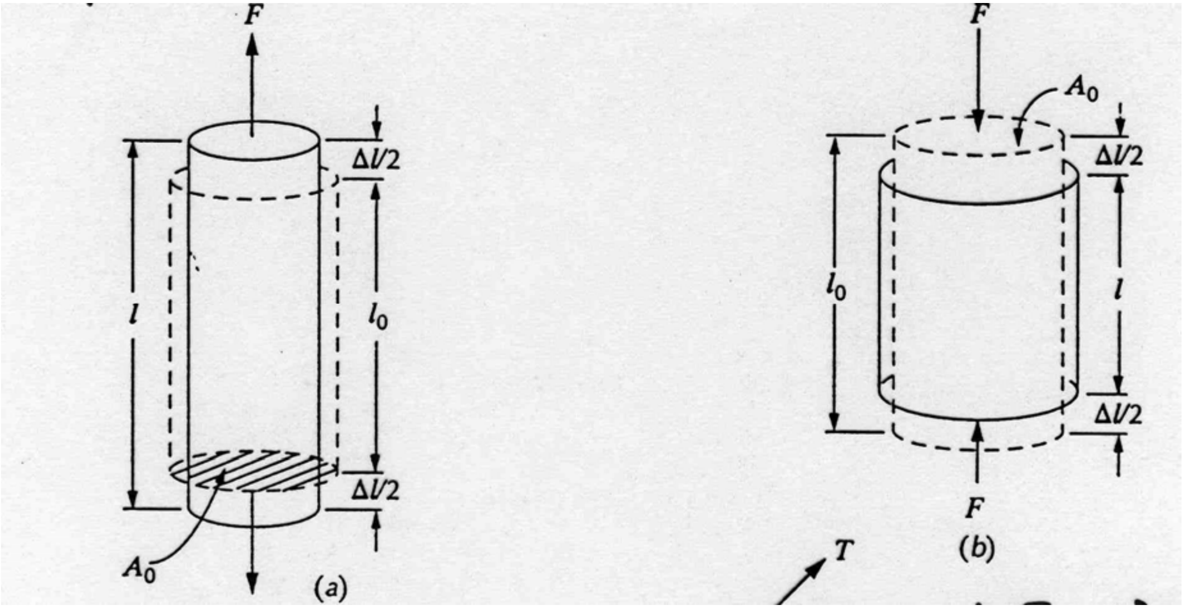


Compression

The figure below shows a composite under a compressive load. Here, the adhesive and stiffness properties of the resin system are crucial, as it is the role of the resin to maintain the fibres as straight columns and to prevent them from buckling.

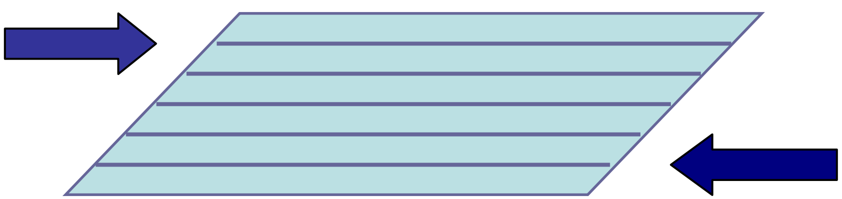


Tension Compression



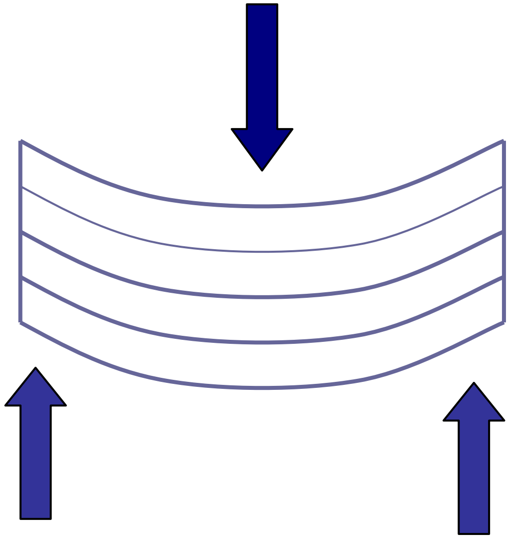
Shear

The figure below shows a composite experiencing a shear load. This load is trying to slide adjacent layers of fibres over each other. Under shear loads the resin plays the major role, transferring the stresses across the composite. For the composite to perform well under shear loads the resin element must not only exhibit good mechanical properties but must also have high adhesion to the reinforcement fibre. The interlaminar shear strength (ILSS) of a composite is often used to indicate this property in a multi-layer composite ('laminate'). .



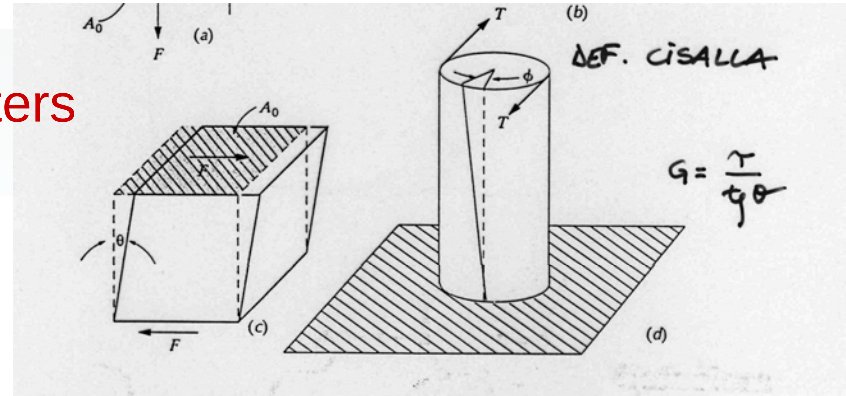
Flexure

Flexural loads are really a combination of tensile, compression and shear loads. When loaded as shown, the upper face is put into compression, the lower face into tension and the central portion of the laminate experiences shear.



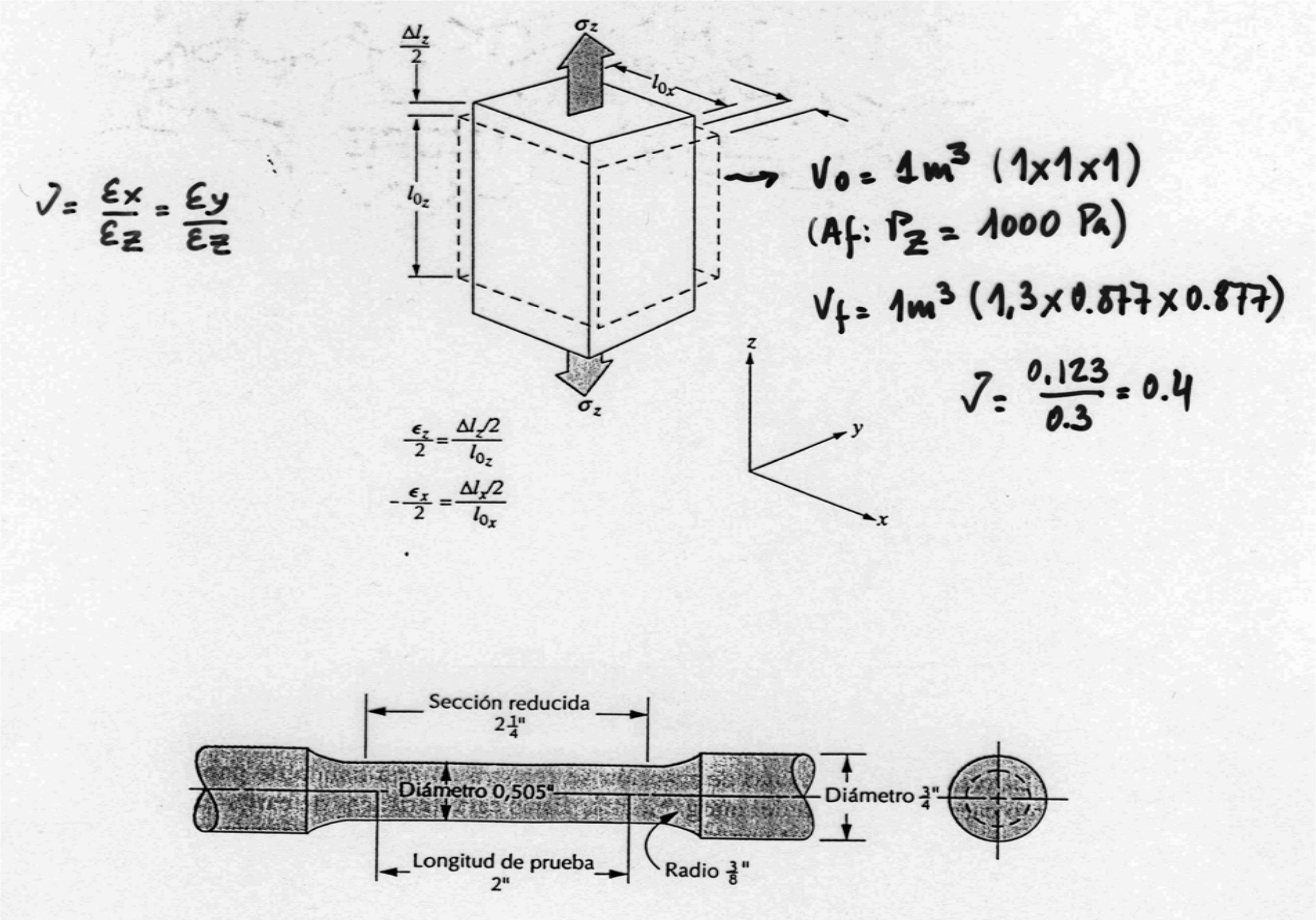
Relation between mechanical parameters

Basic Concepts



compression	$K = \frac{E}{3(1-2\nu)} = \frac{2}{3}\frac{G(1+\nu)}{1-2\nu} = \frac{1}{3}\frac{E}{3-E/G}$
Shear load	$G = \frac{E}{2(1+\nu)} = \frac{3}{2}\frac{K(1-2\nu)}{1+\nu} = \frac{E}{3-E/3G}$
elastic	$E = 2G(1+\nu) = 3K(1-2\nu) = \frac{3G}{1+G/3K}$
poisson	$\nu = \frac{1}{2} - \frac{E}{6K} = \frac{1}{2}\frac{E}{G-1} = \frac{1-2G/3K}{2+2G/3K}$

Poisson's coeficient (ν)



Typical Properties of Some Engineering Materials

Material	Density (ρ) (g/cc)	Tensile Modulus (E) (GPa)	Tensile Strength (σ) (GPa)	Specific Modulus (E/ρ)	Specific Strength (σ/ρ)	Max. Service Temp. (°C)
Metals						
Cast iron, grade 20	7.0	100	0.14	14.3	0.02	230–300
Steel, AISI 1045 hot rolled	7.8	205	0.57	26.3	0.073	500–650
Aluminum 2024-T4	2.7	73	0.45	27.0	0.17	150–250
Aluminum 6061-T6	2.7	69	0.27	25.5	0.10	150–250
Plastics						
Nylon 6/6	1.15	2.9	0.082	2.52	0.071	75–100
Polypropylene	0.9	1.4	0.033	1.55	0.037	50–80
Epoxy	1.25	3.5	0.069	2.8	0.055	80–215
Phenolic	1.35	3.0	0.006	2.22	0.004	70–120
Ceramics						
Alumina	3.8	350	0.17	92.1	0.045	1425–1540
MgO	3.6	205	0.06	56.9	0.017	900–1000
Short fiber composites						
Glass-filled epoxy (35%)	1.90	25	0.30	8.26	0.16	80–200
Glass-filled polyester (35%)	2.00	15.7	0.13	7.25	0.065	80–125
Glass-filled nylon (35%)	1.62	14.5	0.20	8.95	0.12	75–110
Glass-filled nylon (60%)	1.95	21.8	0.29	11.18	0.149	75–110
Unidirectional composites						
S-glass/epoxy (45%)	1.81	39.5	0.87	21.8	0.48	80–215
Carbon/epoxy (61%)	1.59	142	1.73	89.3	1.08	80–215
Kevlar/epoxy (53%)	1.35	63.6	1.1	47.1	0.81	80–215

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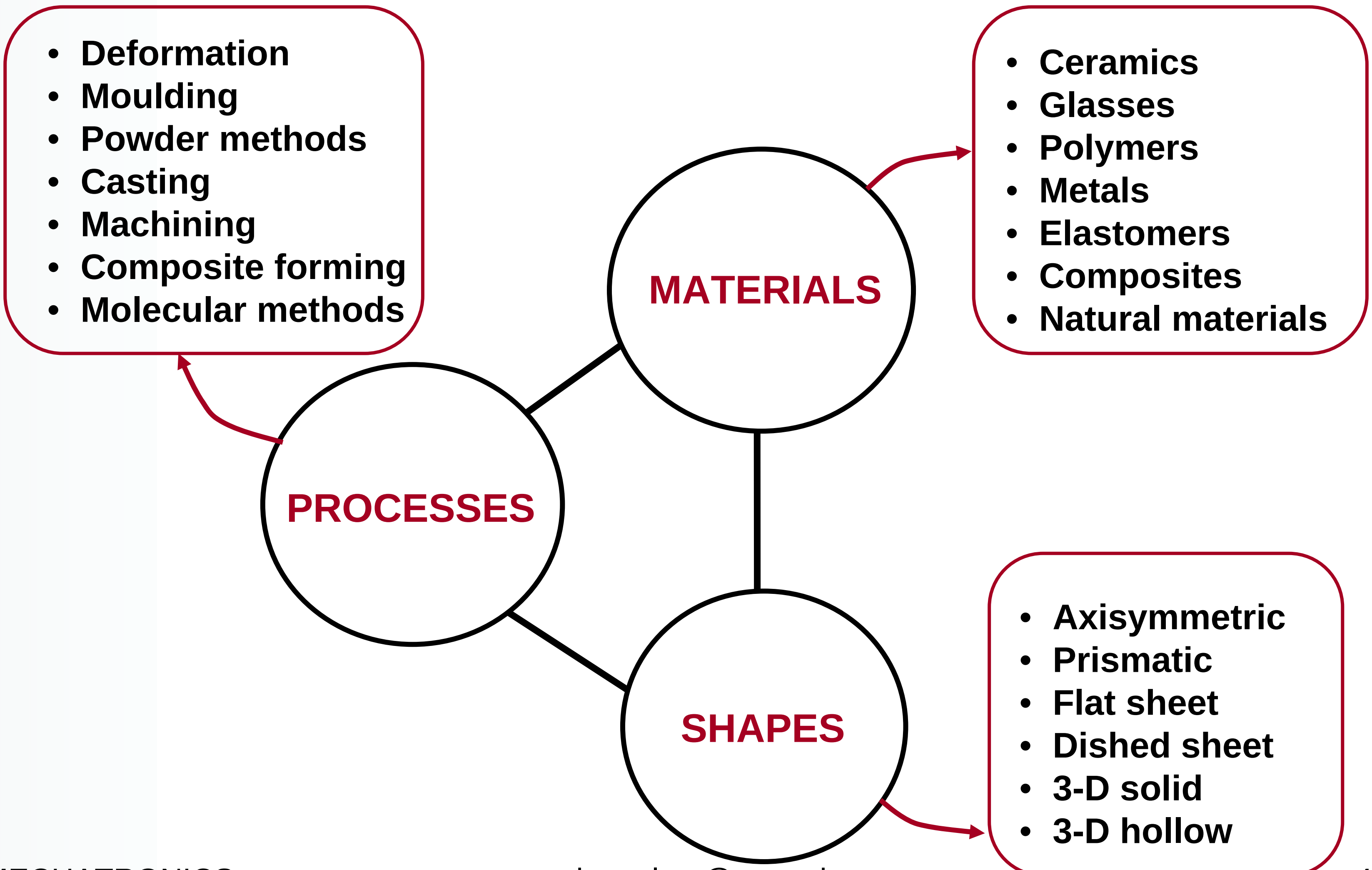
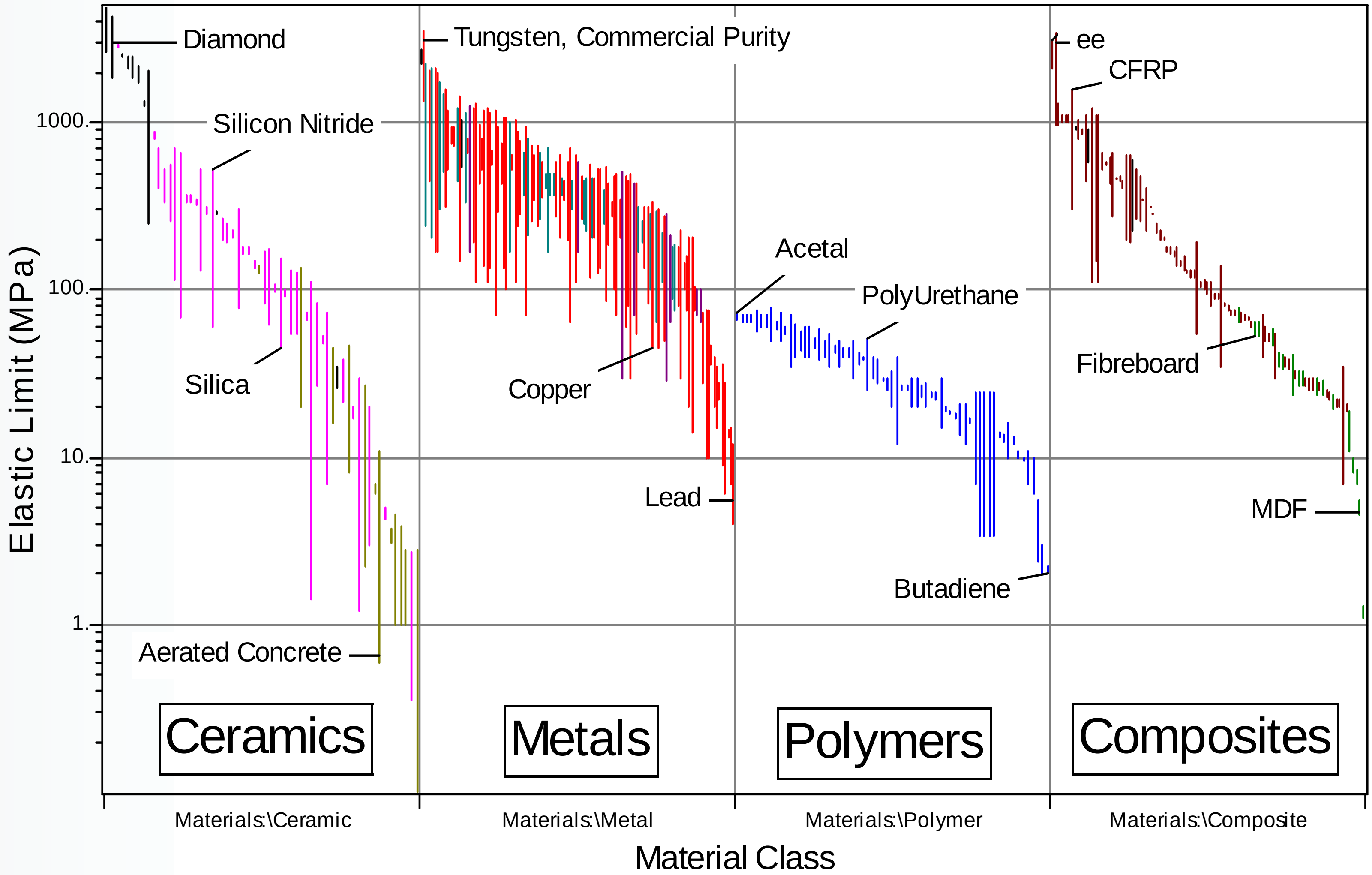
How design a composite material?

Materials, Processes and Shapes

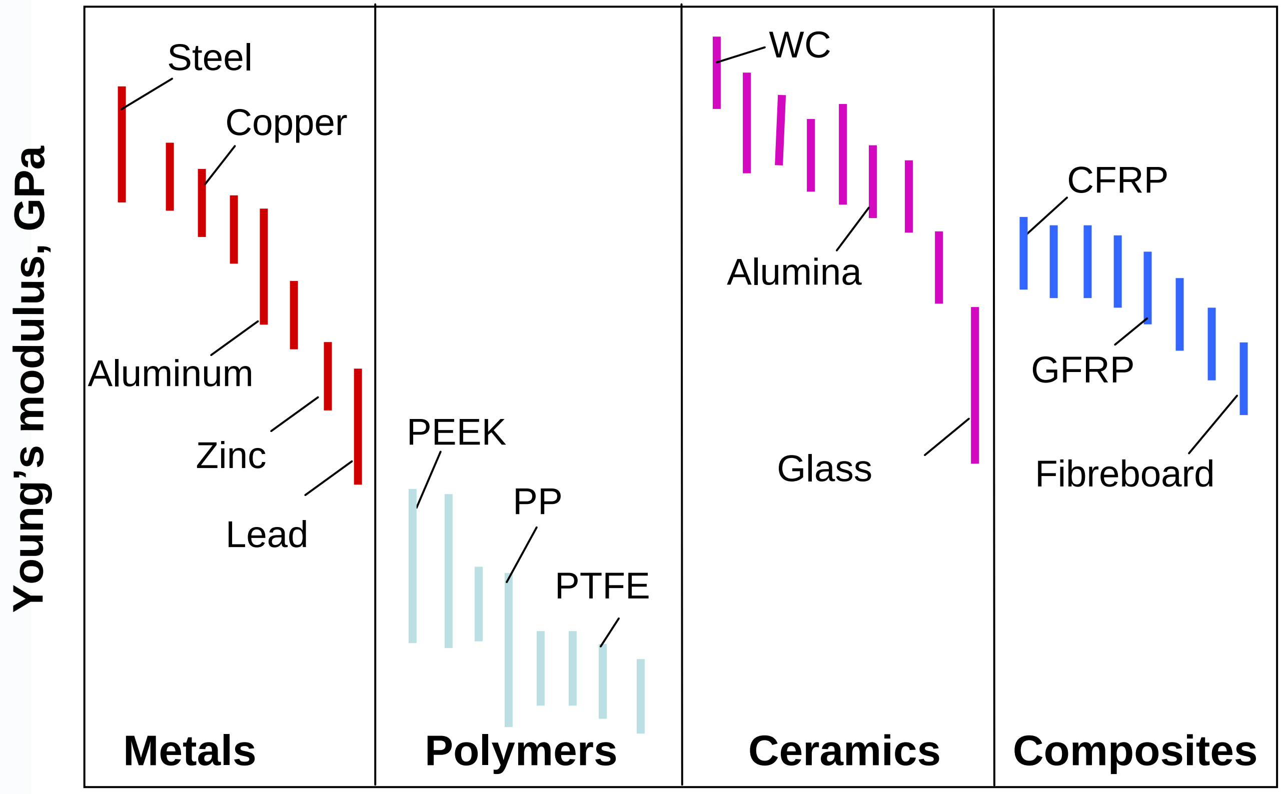


Basic Concepts



How design a composite material?

Relationship between different materials



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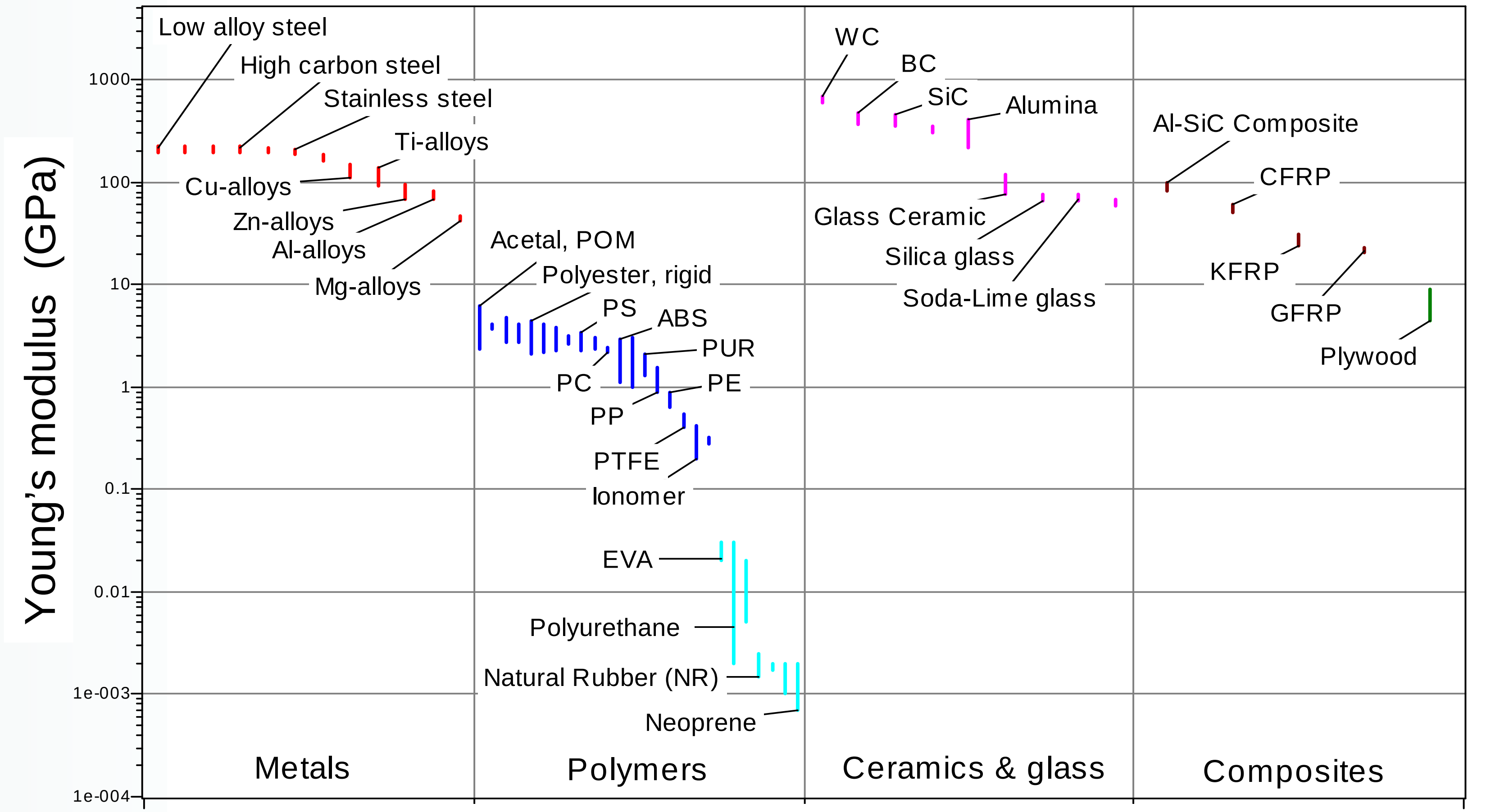
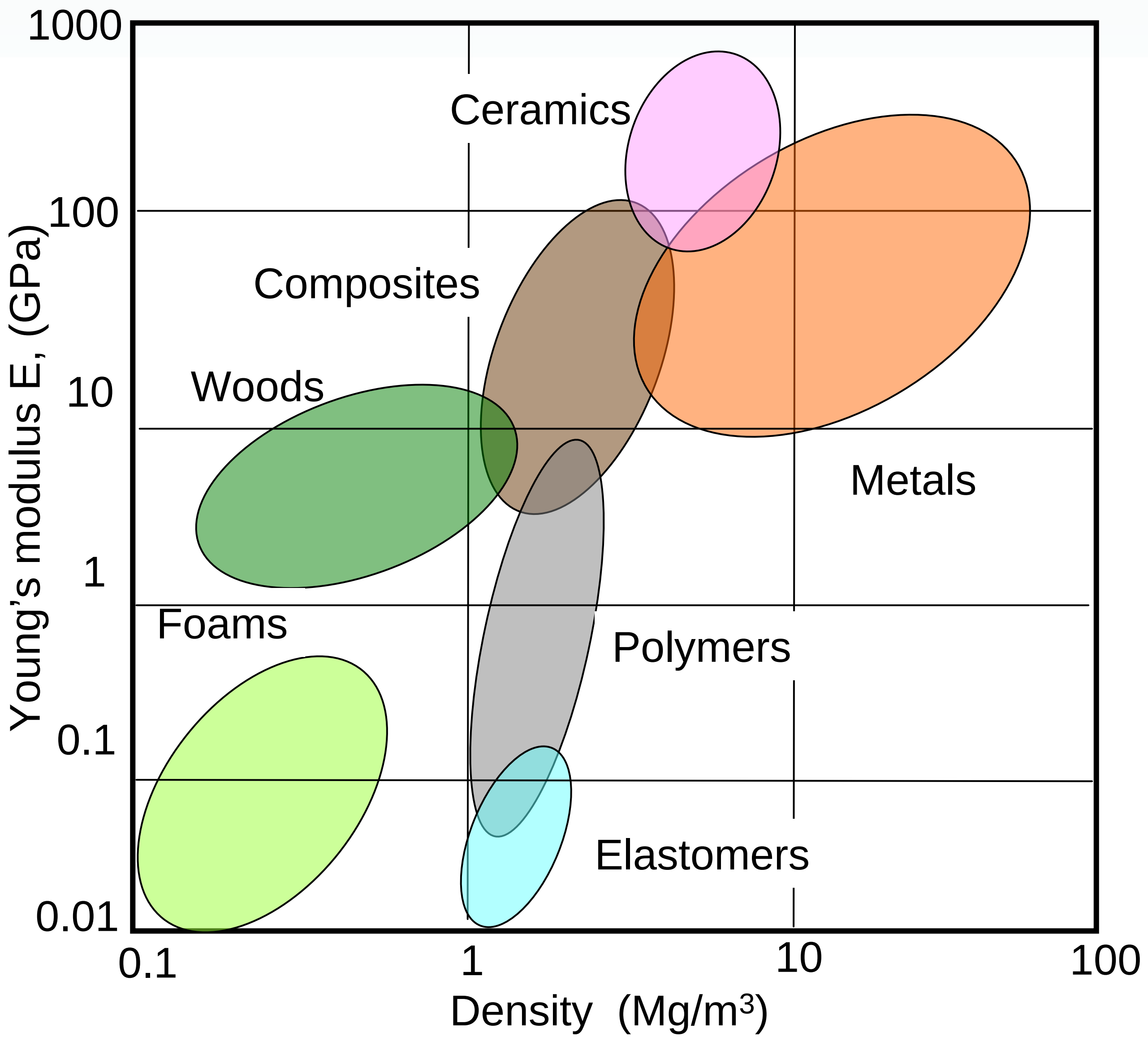
How design a composite material?

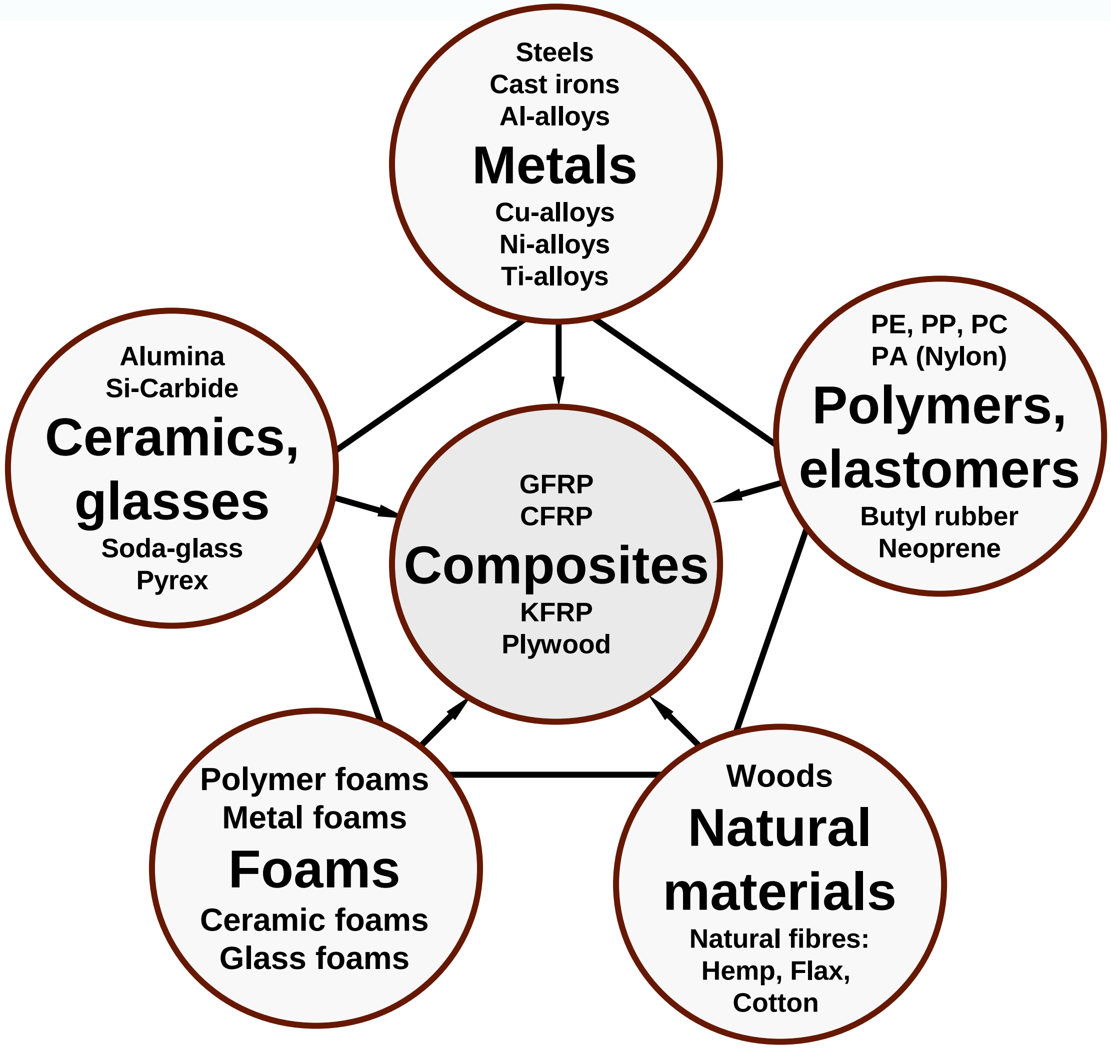
Basic Concepts



How design a composite material?



How design a composite material?



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DFM: Design for Manufacturing

Basic Conce

At Storage Technology, a new assembly using DFM that costs 86% less, reduced part count from 100 to 36. DFM applied to large hydraulic cylinders at Caterpillar, Inc. produced significant cost reduction. Then, at Xerox, DFM was used to re-design a paper feed guide to go from five parts plus hardware to one part and snap fits. Standardized components at IBM help expedite product development.

Fundamentals of Manufacturing Cell Planning

Basic C

The ability to effectively plan a manufacturing cell is a fundamental skill needed by every supervisor, team leader, and manufacturing engineer, This video is based upon a proven and widely used method called Systematic Planning of Manufacturing Cells (SPMC). Together these materials comprise a ready to use kit for introducing, expanding, and improving the use of cells in your plant.