Universidad
Carlos III de Madrid
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MATERIALS SCIENCE AND ENGINEERING

TOPIC 8. COMPOSITE MATERIALS

1. Classification according to type of reinforcement and matrix
2. Type of constituents
3. Particle reinforced composite materials
4. Rule of mixtures
5. Fiber reinforced composite materials
   - 5.1 Types of fibers (glass, carbon, aramid, boron and ceramics)
6. Structural composite materials (laminates and sandwich structures)

DEFINITION AND TYPES

"Mix of two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure"

1. CLASSIFICATION

Reinforcement:

- Particles *(dispersion strengthened or large particles)*
- Fibers *(discontinuous - short or continuous - aligned)*
- Structural *(laminates and sandwich structures)*

Matrix:

- Metal matrix composites (MMC)
- Ceramic matrix composites (CMC)
- Polymer matrix composites (PMC)

When is a material considered to be a composite?

Microstructural level (< 0,01 cm) to macrostructural (> 0,01 cm)

	?	
Wood		**Concrete**
Hypoeutectoid steel		**Reinforce concrete**
Austenitic stainless steel		**Cement**
Cellophane		**Reinforced plastic**
Paper		

DEFINITION AND TYPES

Wood (lignin + celullose)

Concrete (gravel + cement)

Hypoeutectoid steel (ferrite + pearlite)

Reinforced concrete (gravel + cement + steel)

Austenitic stainless steel (grains =)

Cement

Cellophane (Multiple polymeric layers)

Reinforced plastic (it doesn’t improve its properties)

Paper (only cellulose fibers)

- Composite material
- Limit of composite material
- Not a composite material

COMPOSITES IN NATURE

Sea shells

Abalone shell:

$CaCO_3$

+ 3% organic material

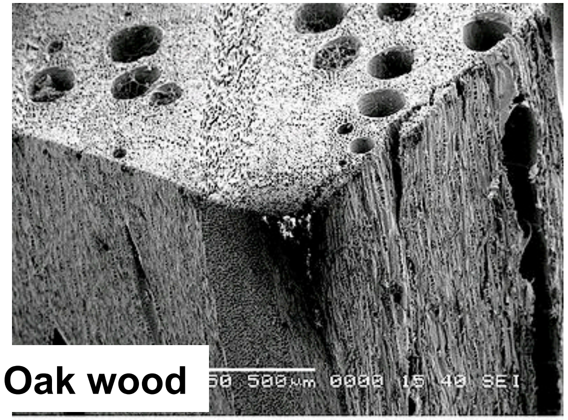
>3000* stronger than calcite

Wood

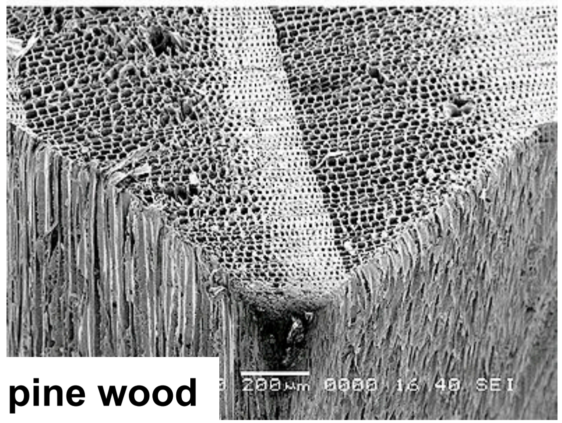
cellulose-filaments in a matrix of lignin and hemicellulose

growth rings form a layered composite

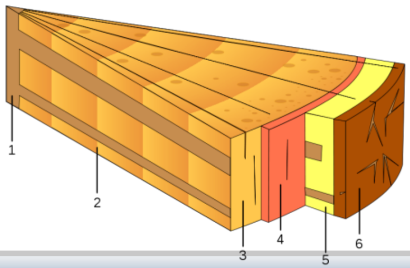
perpendicular to the growth rings are radially oriented ribbon-like structures : rays which provide a redial stiffening and reinforcement



Oak wood



pine wood



http://commons.wikimedia.org/wiki/File:Wood_structure_numbers.svg
http://commons.wikimedia.org/wiki/File:Hard_Soft_Wood.jpg

CLASSES ACCORDING TO REINFORCEMENT AND MATRIX

Different matrix, reinforcement and properties of CM		
Matrix	**Reinforcement material**	**Properties**
Metal	Metal fibers, ceramic, carbon, glass	Electric resistance to temp.↑ thermal stability
Ceramic	Particles and metallic fibers and ceramics	Chemical and thermal resistance to temp. ↑
Glass	Glass and ceramic particles	Mechanical strength and chemical resistance to temp.↑ thermal stability
Organic	Carbon, glass and organic fibers	Mechanical strength to high temp. chemical and electrical, and erosion resistance, flexibility and thermal stability

Properties to take into account for material design ⇒

- **For ceramic and metallic component: Physical (thermal, electrical, optical…) and mechanical (stiffness, toughness, stress-strain behaviour…)**
- **For plastic components: Physical and mechanical. Also the water absorption and transmission**

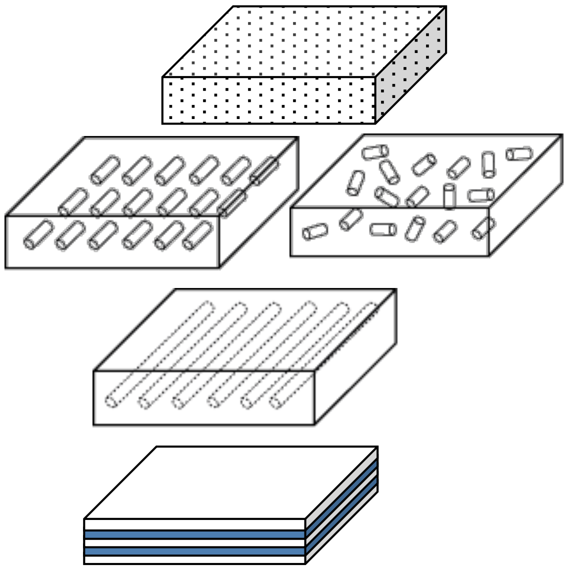
TYPE OF CONSTITUENTS

Structures, reinforcements, types and properties of composite materials

COMPOSITE MATERIALS

- Particle-reinforced
  - Large-particle
  - Dispersion strengthen
- Fiber-reinforced
  - Continuous (aligned)
  - Discontinuous (short)
    - aligned
    - Randomly oriented
- Structural
  - Laminates
  - Sandwich panels

Structure

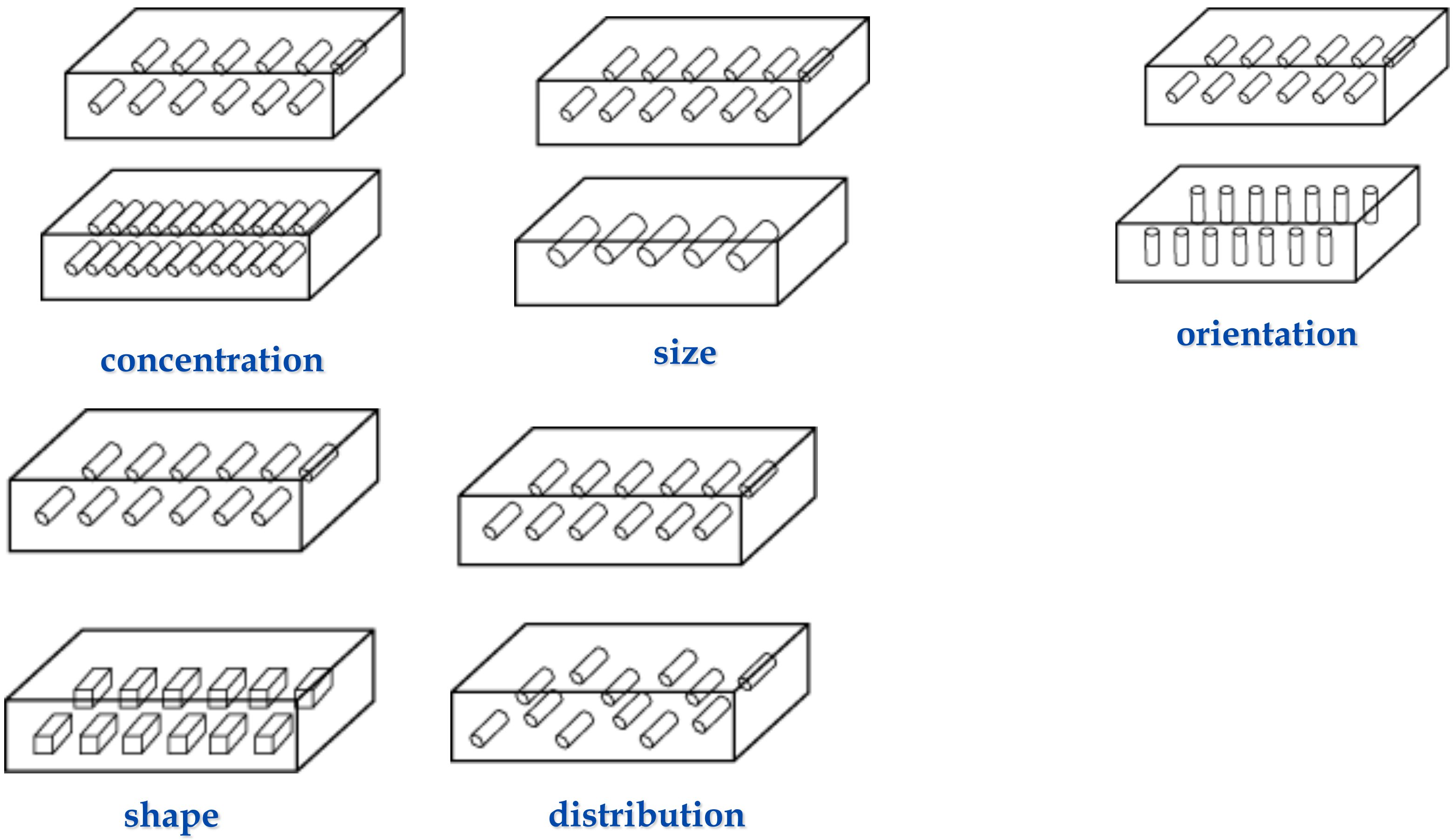


Reinforcement	Composite material	Properties
Particles	Particle-reinforced	Isotropic
Short fibres	Random Aligned	Isotripic Anisotropic
Continious fibers	Aligned continous fibres	Anisotropic
Laminates or layers	laminates	Anistotropic

TYPE OF CONSTITUENTS

The composite material properties depend upon the properties of each of its phases, their relative proportions and their geometry

Schematic representation of several geometric and spatial characteristics of particles of the dispersed phase



3. PARTICLE-REINFORCED COMPOSITE MATERIALS

Particles: geometrical variety

Factors that have an influence in physical an mechanical properties:

size, distribution and particle content

General aspects of particle reinforce composites:

- **Advantages of particle reinforced composite materials**
  - **Low cost**
  - **High stiffness and strength (inorganic particles)**
  - **Wear resistance**
  - **Simpler manufacturing process**
- **Mechanical properties depend on the reinforcement, manufacturing and subsequent treatments**
- **Most used metallic matrixes are Al, Mg, Ti y Ni**
- **Polymeric matrixes are reinforced to improve their mechanical strength and abrasion resistance**

3. PARTICLE-REINFORCED COMPOSITE MATERIALS

TYPES OF PARTICLES

Great variety of ceramic particles

To select the appropriate reinforcement it should be taken into account:

- Structural
  - High modulus
  - Low density
  - Particle shape (avoid corners)
- Thermal:
  - Expansion coefficient and conductivity

Properties of SiC and Al_2O_3 particles:

Particle	E (GPa)	ν	ρ (g/cm^3)	α (K^{-1})	K ($Wm^{-1}K^{-1}$)
SiC	420-450	0.17	3.2	4.3×10^{-6}	10-40 a 1100ºC
Al_2O_3	380-450	0.25	3.96	7.0×10^{-6}	5-10 a 1000ºC

3. PARTICLE-REINFORCED COMPOSITE MATERIALS

⇒ Dispersed phase: Particles with d=10-250 nm ⇒ Dislocation movement is blocked causing hardening (↑ hardness, ↑ E, ↑ σ).

⇒ Continuous phase: Matrix is bearing the load

Examples and applications of dispersion strengthened compounds

System	Application
Ag-CdO	Electrical connectors
Al-Al_2O_3	Nuclear reactors
Be-BeO	Nuclear reactor and aerospace
Co-ThO_2, Y_2O_3	Magnetic materials resistant to yield
Ni-20% Cr-ThO_2	Turbojet components
Pb-PbO	Battery grid
Pt-ThO_2	Wires, electrical components

3. PARTICLE-REINFORCED COMPOSITE MATERIALS

3.2 Composite materials reinforced with large particles

⇒ Large particles of a hard and brittle material uniformly scattered in soft and ductile matrix. Meso-micro scale. The reinforcement bears or helps to bear the load.

⇒ These composites are designed to produce unusual properties and not to improve strength

- **Metals and ceramics** ⇒ *particles are added to improve toughness and mechanical resistance*
- **Plastics** ⇒ *particles are added as a filling to improve properties (carbon black - soot, elastomers) or reduce cost (CO_3Ca, clays, hollow glass spheres…)*

3. PARTICLE-REINFORCED COMPOSITE MATERIALS

CERMETS (cemented carbides) Hard ceramic particles scattered in a metallic matrix

Tungsten carbide particles, WC (hard, stiff, and ↑T_m) scattered in metallic matrixes are used as cutting tools

These composites are brittle ⇒ toughness improvement: it is combined with Co powder that when sintered acts as an adhesive for WC particles.

ABRASIVE cutting and forming discs from alumina Al_2O_3, silicon carbide, SiC cubic boron nitride, BN. This particles are cemented in vitreous or polymeric matrixes

CAST PARTICLE REINFORCED COMPOSITES Al casting with SiC particles for applications in the car industry (pistons and connecting rods)

3. PARTICLE-REINFORCED COMPOSITE MATERIALS

CONCRETE

It is a matrix of cement together with gravel or sand particles

"It is a composite of particles held together by cement"

There are two kinds of cement: Asphalt cement (for paving) and Portland cement (for building construction)

PORTLAND CEMENT CONCRETE

Ingredients: Fine aggregate Portland cement (sand), coarse aggregate (gravel) and water

⇒ fine sand particles occupy the empty spaces between gravel particles. These aggregates are 60-80% of the total volume.

⇒ The cement-water mixture must cover the sand and gravel particles. The final bonding cement-particles depends upon the quantity of water (insufficient water: incomplete bonding; excess water: porosity)

PROBLEMS: low strength and extremely brittle; it dilates and contracts with temperature; cracks appear when it undergoes freezing-defreezing cycles.

SOLUTION: Reinforcements REINFORCED CONCRETE (STEEL tubes, bars, wires or meshes in cement before curing)

3. RULE OF MIXTURES

Rule of mixtures: The properties of a composite material depend upon the relative quantities and properties of its constituents

$$P_{CM} = \sum f_i p_i$$

P_{CM}= Properties of the composite material;

f= volumetric fraction of each i ($\sum f_i$=1)

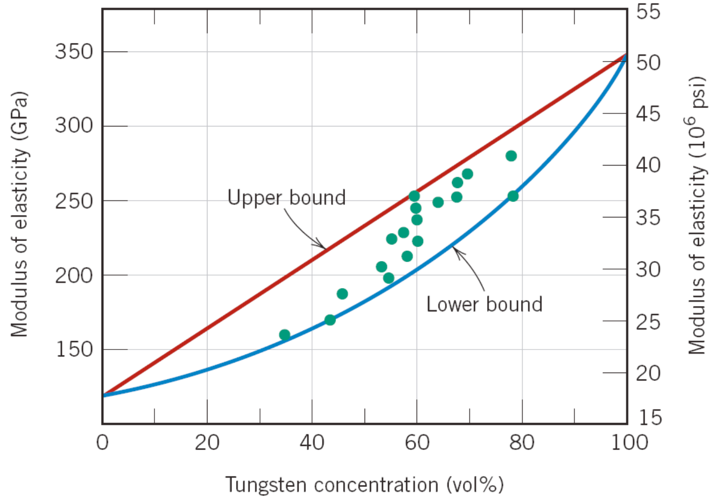
i= i-th component

Particle-reinforced composite → *Isotropic properties*

Relationship between volume fraction and E ⇒"Value of E constrained"

Maximum: $$E_C = E_p V_p + E_m V_m$$

Minimum: $$E_C = \frac{E_p E_m}{V_p E_m + V_m E_p}$$

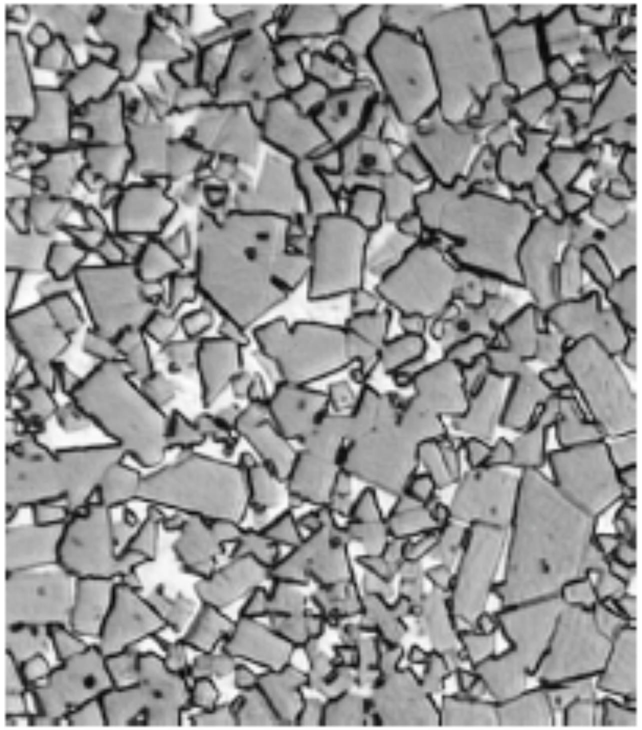


William D. Callister, Jr. ,Materials Science and Engineering: An Introduction, John Wiley & Sons, Inc.

E: elastic modulus
V: fraction of volume
m: matrix
p: reinforcement
c: composite material

Examples: Particle Reinforced composite

Carbon Black particle reinforcement in Styrene-Butadiene synthetic rubber for car tire application.



WC–Co cemented carbide. Light areas are the cobalt matrix; dark regions, the particles of tungsten carbide x100.

William D. Callister, Jr. ,Materials Science and Engineering: An Introduction, John Wiley & Sons, Inc.

5. FIBER-REINFORCED COMPOSITE MATERIALS

"High performance composite materials"

Soft and ductile matrix + Strong, rigid and brittle fibers can achieve:

improved wear resistance, stiffness and better strength-weight relationship

Goal: high stiffness and strength with low density

⇒*Specific strength and specific modulus*

a) Role of the fibers

⇒ Bear most of the load applied

Types of fibers ⇒ To reinforce plastics: glass (GRP), carbon (CFRP) y, aramide (AFRP) Other fibers: boron, SiC, Al_2O_3

GOOD BONDING FIBERS ⇔ MATRIX IS REQUIRED

b) Role of the matrix

⇒Transfers external load among fibers

⇒Prevents chemical and abrasive degradation of the fibers

⇒Prevents crack propagation

⇒Keeps fiber orientation

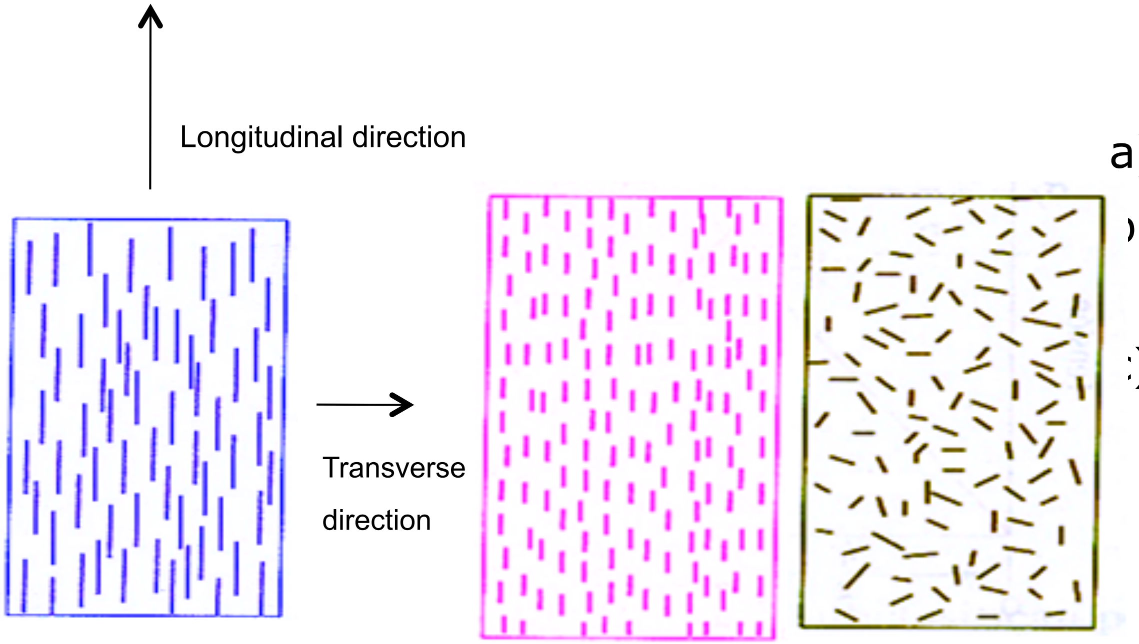
Types of matrix*:* Polymeric: epoxy (for continuous fibers) and polyester (for short fibers) ; metallic and ceramic (less used)

5. FIBER-REINFORCED COMPOSITE MATERIALS

Classification according to shape

Continuous fibers (aligned)

Short or discontinuous fibers (aligned or randomly scattered)

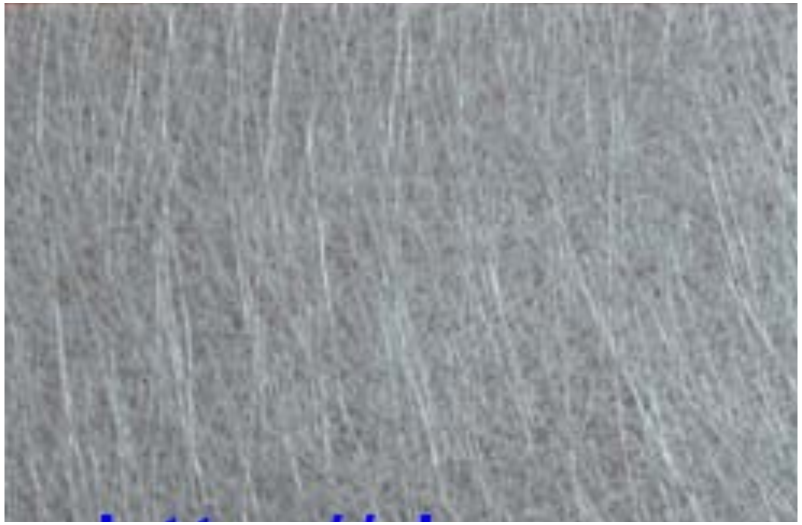


a)Continuous and aligned fibers

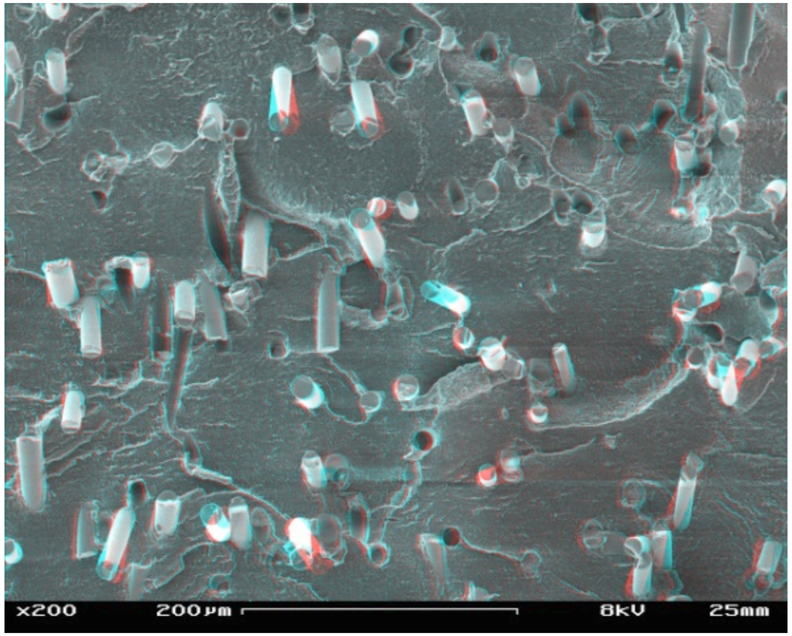
)Discontinuous and aligned fibers

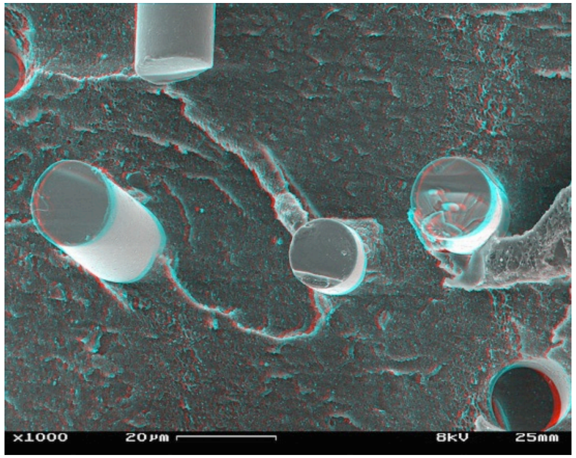
:)Discontinuous and randomly places fibers

5. FIBER-REINFORCED COMPOSITE MATERIALS



Glass Fibers





Composite material fiberglass reinforced polymeric matrix ***(stereoscopic SEM image of the fracture surface)***

http://commons.wikimedia.org/wiki/File:Glass_reinforced_plastic_SEM_Stereo_200x.JPG

5.1 TYPES OF FIBERS: Glass Fibers

Used to reinforce plastic matrixes

Composition: Base of SiO_2 (50-70%) + Oxides Ca, Al, B, Na, Mg and K

Properties: non combustible, good chemical, biological and thermal resistance ($T_m \uparrow, \alpha \downarrow$), thermal insulator ($K \downarrow$), electric insulator ($\sigma \downarrow$), low expansion coefficient and low cost

Types and composition of different fiberglass:

	Material, % in weight							
Type of glass	Silica	Alumina	Ca Oxide	Magnesium	B Oxide	Na_2CO_3	Ca Fluoride	Secondary Oxides
E (1)	54	14	20,5	0,5	8	1	1	1
A (2)	72	1	8	4	-	14	-	1
ECR	61	11	22	3	-	0,6	-	2,4
S (3)	64	25	-	10	-	0,3	-	0,7

(1) Ca Aluminoborosilicate
(2) Rich in alkali
(3) Mg Aluminosilicate without B

5.1 TYPES OF FIBERS: Glass Fibers

Fiberglass properties

Type of glass	$\rho_{relative}$	$\sigma_{tensile}$ (MPa)	E (GPa)	$\alpha \times 10^{-6}$ (K)	ε (a 20 ºC y 1 MHz)	T_m (ºC)	For applications that require
E	2,58	3450	72,5	5,0	6,3	1065	Good electrical properties and dimensional stability (circuit boards)
A	2,50	3040	69,0	8,6	6,9	996	Chemical resistance
ECR	2,62	3625	72,5	5,0	6,5	1204	Good electrical properties and chemical resistance
S	2,48	4590	86,0	5,6	5,1	1454	Tensile strength and thermal stability (aerospace and aeronautic industries)

- **The strength of these fibers is high but not extreme: there are limits in their application**
- **E glass is the cheapest and has the highest moisture resistance (polymeric matrixes)**
- **All the fibers are good insulators**

Common polymeric matrixes:

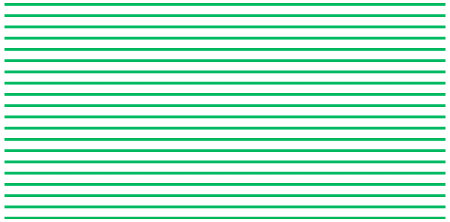
Thermoplastics: Nylon 66, Polycarbonate y Polystyrene

Thermoplastics: Epoxy, polyesters, phenolic, silicon

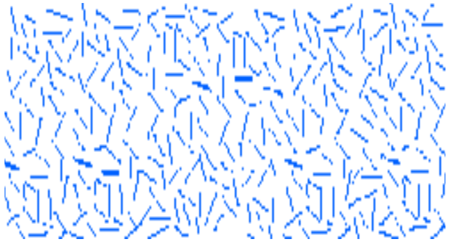
5.1 TYPES OF FIBERS: Glass Fibers

There are three possible configurations for fiberglass reinforced composite materials:

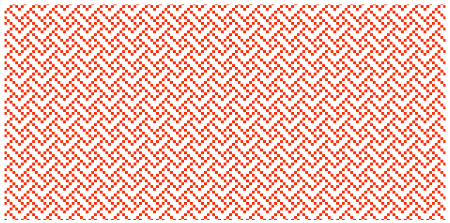
a.

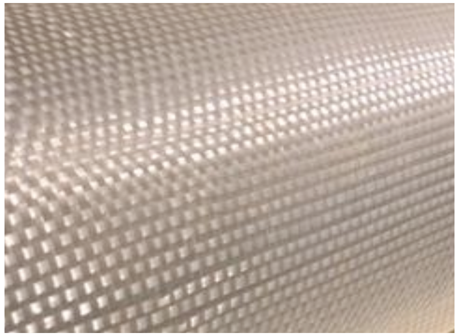


b.



c.





a) Continuous fibers
b) Discontinuous
c) Woven fiber (for laminated structures)

5.1 TYPES OF FIBERS: Carbon fiber

Advanced composites for aerospace and aeronautic fibers

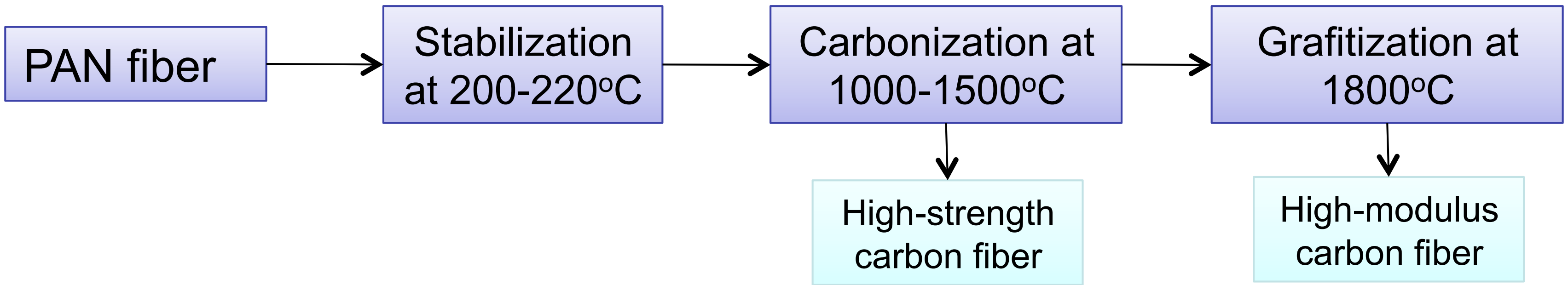
⇒**Very good thermal and physical properties** (High electrical conductivity and high thermal conductivity).

⇒ **Carbon fibers** in composites with plastic resins (i.e.: epoxy) good combination of high mechanical strength, stiffness and low weight →aerospace applications

-Low cost: *sport equipment manufacturing, industrial and commercial products (70's ≈ 220 $/kg and 80's ≈ 9$/kg)*

⇒ **Manufactured from organic precursors***:*

- ***Rayon and isotropic tars (fibers E↓ , ≤ 50 GPa)***
- ***Polyacrylonitrile (PAN) and liquid crystal tar (E↑) (easier to orientate)***

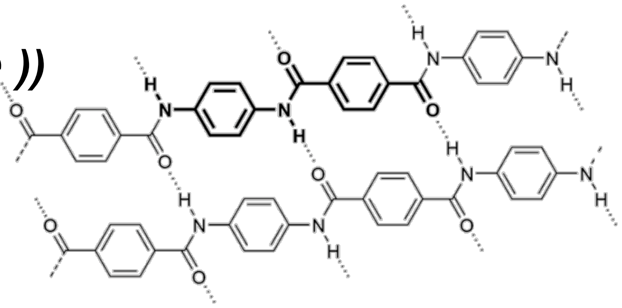


1. **STABILIZATION Stretching (200-300ºC): fibrillar network**
2. **CARBONIZATION 1000-1500ºC inert atmosphere ⇒ Removal O,H,N HT-CF**
3. **GRAPHITIZATION T>1800ºC. Degree of orientation increased: ↑E and strength: HM-CF**

5.1 TYPES OF FIBERS: Aramid fiber

⇒ ***Kevlar polyamide (poly(****paraphenylene terephthalamide))***

⇒***The aromatic ring provides thermal stability***



http://commons.wikimedia.org/wiki/File:Kevlar_chemical_structure_H-bonds.png

⇒ **E ↑↑ due to its configuration:** ***rigid molecules are arrayed in ordered domains (liquid crystal polymer)→ during extrusion they are oriented in the direction of the flow***

⇒ ***Thermal and electrical insulator, ↓α, high impact strength and ↓E (compared to carbon)***

Types of Kevlar fibers (commercially introduced in 1972 by Du Pont):

Kevlar 49 → ***most used structural composite due to its ↑E***
Kevlar 29 → ***high toughness applications (i.e.: bulletproof jacket)***
Kevlar 149 → ***value of E ≈ theoretical***

Properties of the three types of Kevlar					
Material	ρ (g/cm^3)	D_{wire} (μm)	$\sigma_{tensile}$(GPa)	E (GPa)	ε (%)
Kevlar 29	1,44	12	3,6	83	4,0
Kevlar 49	1,44	12	3,6-4,1	131	2,8
Kevlar 149	1,47	12	3,4	186	2,0

5.1 TYPES OF FIBERS: Boron and ceramics

Boron fibers

Manufactured through a vapor deposition of B over a core of W

⇒ **Properties:** *very high strength and stiffness*

⇒**Applications:** *in Al and Ti matrixes*

⇒ **Limitation:** *Very expensive*

First fibers used as reinforcement

Ceramic fibers: Mainly quartz (Al_2O_3, Si_3N_4,…)

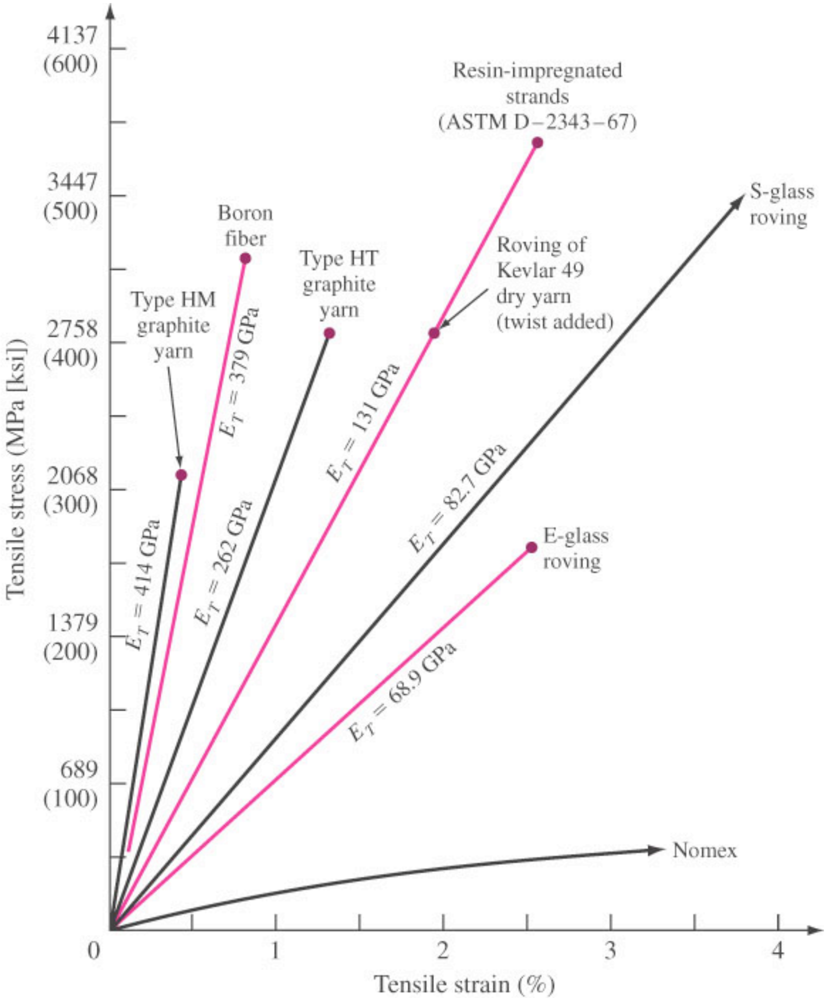
⇒**Properties:** *Can resist high T (T>1300 ºC) and thermal shocks*

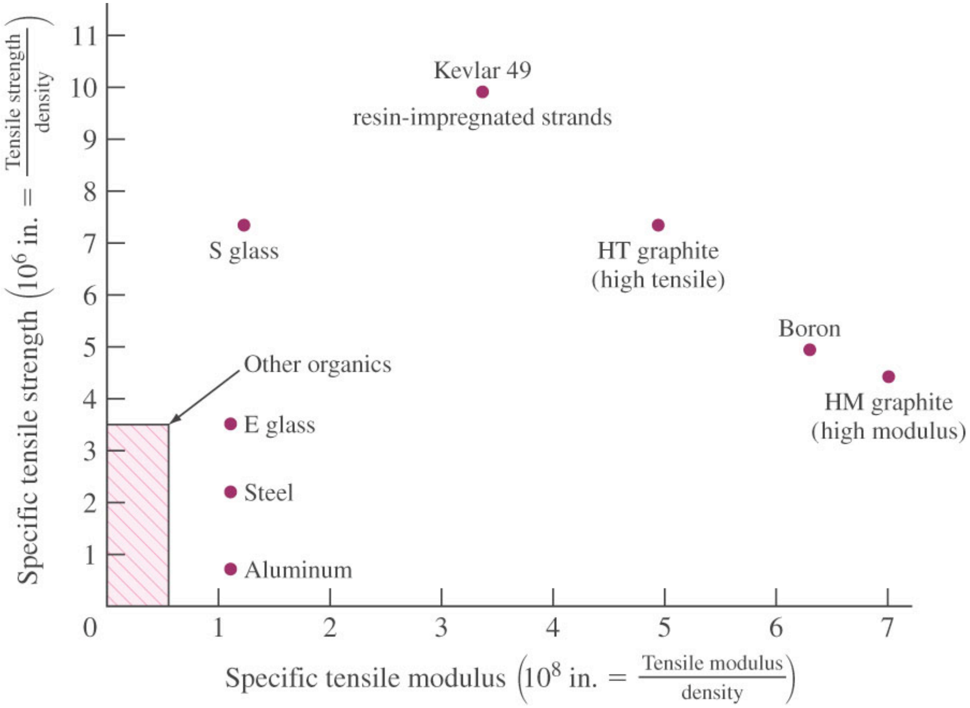
⇒**Applications:** *Thermal insulator. Not structural applications.*

⇒**Limitation:** *very expensive (5 times the price of carbon fiber)*

5.1 TYPES OF FIBERS

Mechanical properties of the different fibers





William F. Smith, Foundations of Materials Science and Engineering, 3/e, McGraw-Hill 2004

6. STRUCTURAL COMPOSITE MATERIALS

- Formed by composite materials and homogeneous materials
- Properties depend on the geometry of the structural elements

Types → laminated composites
→ sandwich structures

6.1. LAMINATED COMPOSITES

Piling of layers or lamina of unidirectional composite material

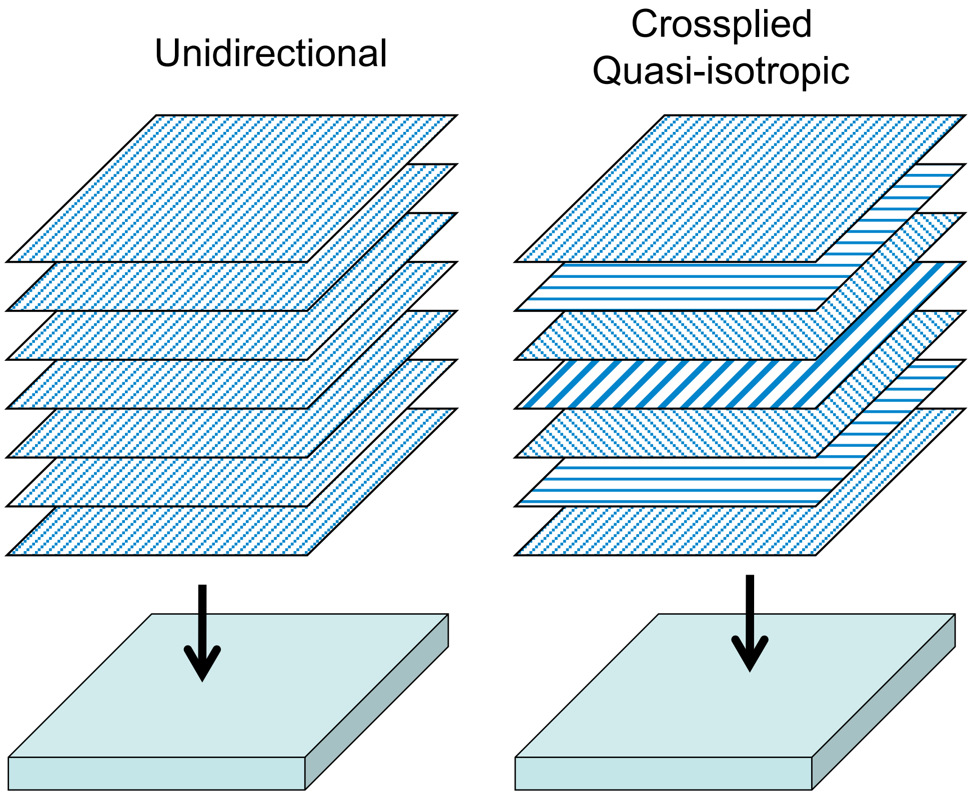
Laminar composite example: *continuous and aligned fiber reinforced plastics with matrixes such as epoxy, polyester, PE, PA, PET…*

In order to get different mechanical properties ⇒ layers of materials with different properties are piled, or a different way of piling layers on top of each other.

6.1. LAMINATED COMPOSITES

⇒Orientation of fibers with respect to the lamina:

- Usual fiber orientations: 0, 90, +/-45. By combining these orientations, the desired strength and stiffness is achieved. Plane isotropy can be achieved.
- Fiber layers arranged in a way so that strength is maximized and weight is minimized.



Piled lamina. The orientation of the direction with ↑R changes in each of the layers

- Laminated composites must always be symmetric with respect to their middle plane, and the must also be balanced to avoid anomalous distortions in the structure
- The strength and stiffness varies greatly with the orientation.
- A piling of woven materials without any bonding does not have any structural use. Therefore a matrix is needed.
- Exclusively unidirectional composites are never used.

6.2. SANDWICH COMPOSITES

2 external strong layers (face sheets) attached to a layer of less dense material (core) with low stiffness and low strength

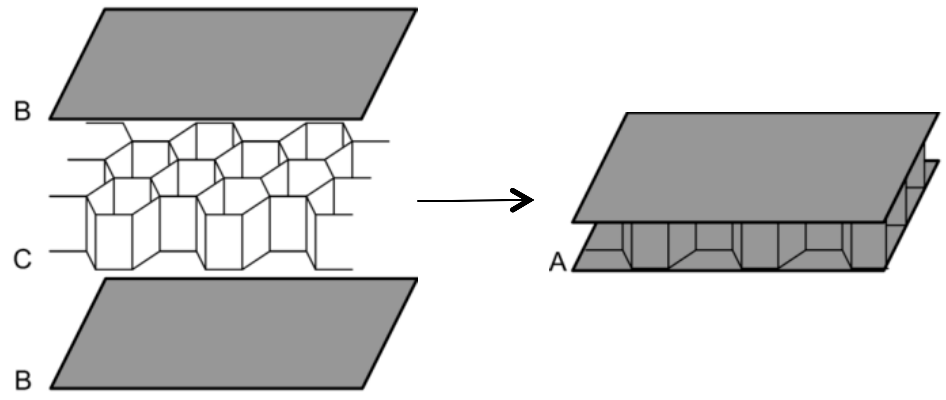
- Role of the face sheets they withstand most of the plane loads and transversal bending stresses
- Face sheet material Al alloys, fiber-reinforced plastics, Ti, steel and plywood.
- Core material *separates* both face sheets and resists deformations perpendicular to the face plane. Provide resistance to shear stress along the planes perpendicular to the face sheets

- **Core materials may have different and have different structures**: polymer foams, synthetic rubber, inorganic cement and balsa wood

- **Typical core with honeycomb structure**→ thin layers arranged in hexagonal cells.

Applications ⇒ *ceilings, floors and walls in buildings, in the aerospace industry (wing coating, fuselage)*

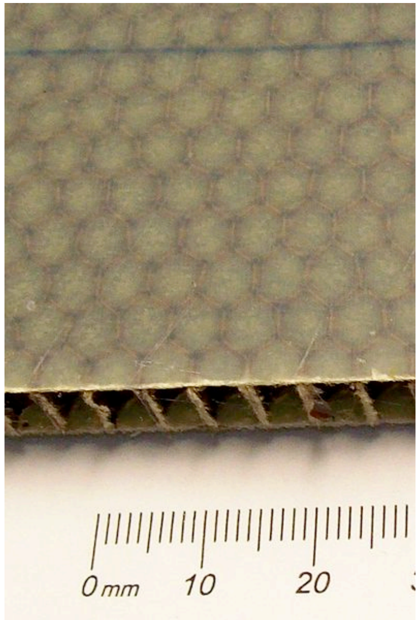
A sandwich panel with a honeycomb core



honeycomb panel used in aircraft

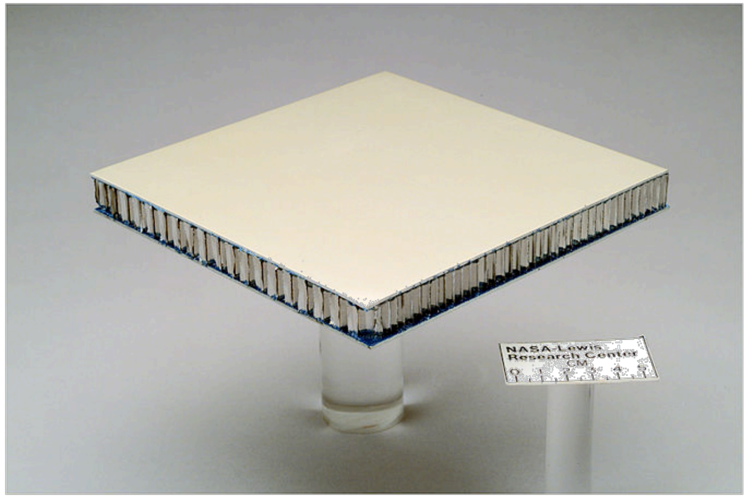
http://commons.wikimedia.org/wiki/File:CompositeSandwich.png

Applications of composites

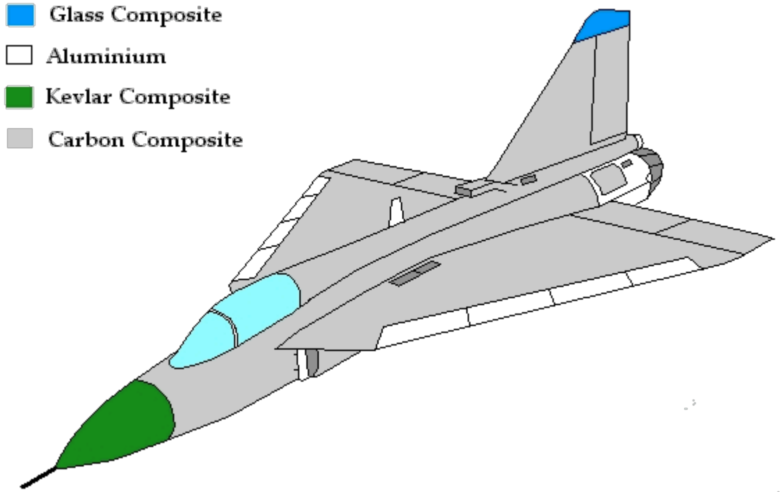


honeycomb panel
used in aircraft

NASA
C-2000-1447



National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field

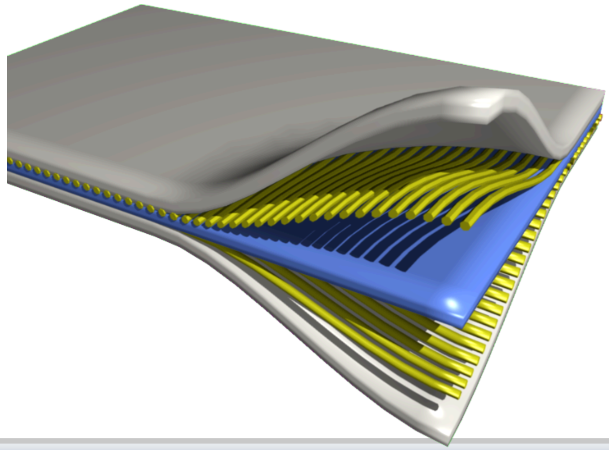


Composites in LCA

http://commons.wikimedia.org/wiki/File:LCA_Composites.jpg

GLARE

"GLAss-REinforced" Fibre Metal Laminate (FML),



Applications of composites