

# MSE 214 Composites A

## Les matériaux composites

- . Les fibres, les matrices
  - . Micromécanique et anisotropie
  - . Les procédés de mise en oeuvre
  - . Les développements récents
- Biocomposites
- Composites auto-réparables
- Nanocomposites

## Références:

TRAITÉ DES MATÉRIAUX

15

MATÉRIAUX  
COMPOSITES  
À MATRICE ORGANIQUE  
Constituants, procédés, propriétés

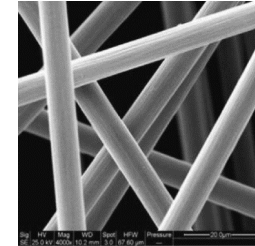
Pierre-Etienne Bourban · Leif Carlsson  
Jean Pierre Mercier · Jan Anders E. Månsson

Traité des Matériaux, vol. 15  
" Matériaux composites à matrice organique"

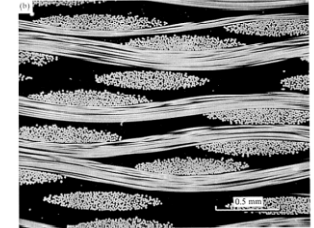
Presse Polytechniques et Universitaires Romandes

EPFL

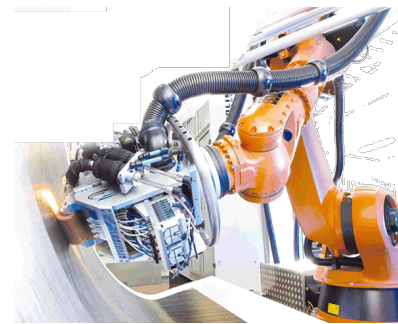
pierre-etienne.bourban@epfl.ch



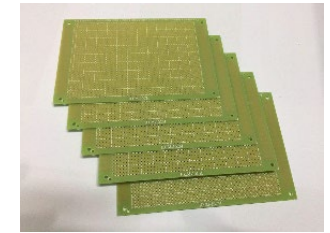
www.reinforcedplastics.com



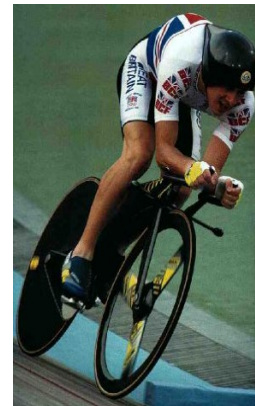
## Des fibres aux stratifiés



www.coriolis-composites.com



Rigidités et anisotropies exploitées



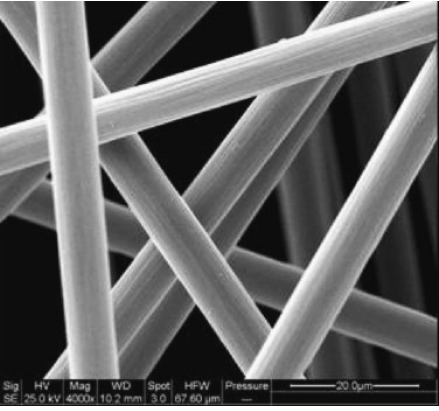
BMW i8 automobile.challenges

# Introduction aux matériaux composites 2025

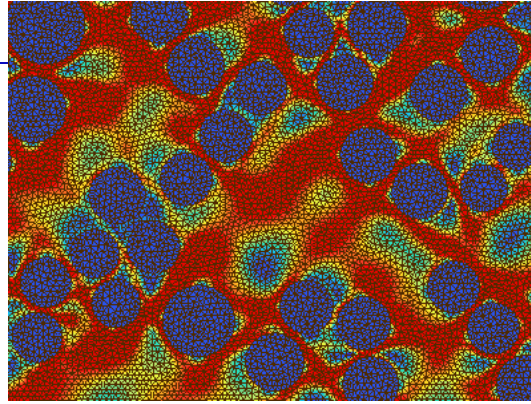
**MSE-214/215 Ingénierie des matériaux**

**pierre-etienne.bourban@epfl.ch**

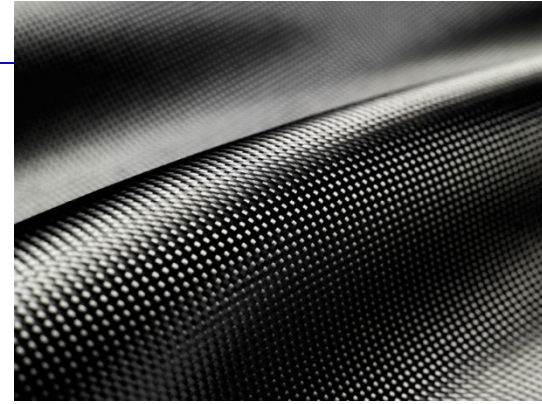
**Institut des matériaux (IMX)  
Discovery Learning Labs (DLL)  
Ecole Polytechnique Fédérale de Lausanne (EPFL),  
CH-1015 Lausanne**



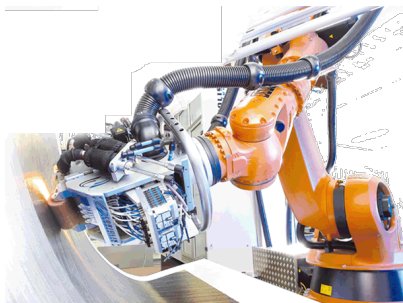
[www.reinforcedplastics.com](http://www.reinforcedplastics.com)



[www.onera.fr](http://www.onera.fr)



[blog.motorlegend.com](http://blog.motorlegend.com)



[www.coriolis-composites.com](http://www.coriolis-composites.com)



Boeing



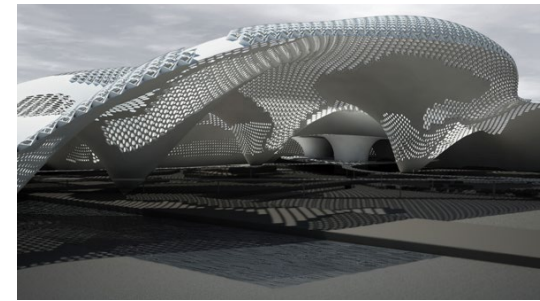
[BMW i8 automobile.challenges](http://BMW i8 automobile.challenges)



[www.decision.ch](http://www.decision.ch)

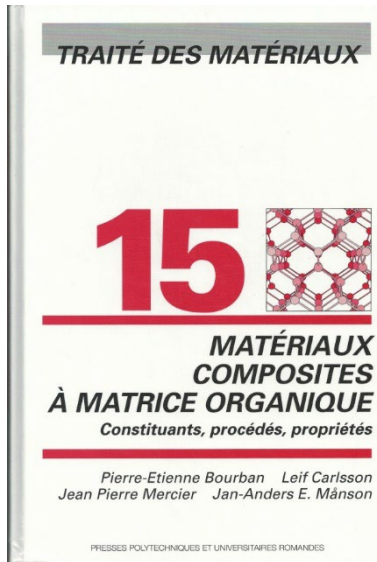


Hublot



[www.evolo.us](http://www.evolo.us)

# Biblio



Traité des Matériaux, vol 15,  
PPUR, EPFL-Lausanne

Comprehensive composite materials,  
Kelly A, Zweben C. ed., Elsevier

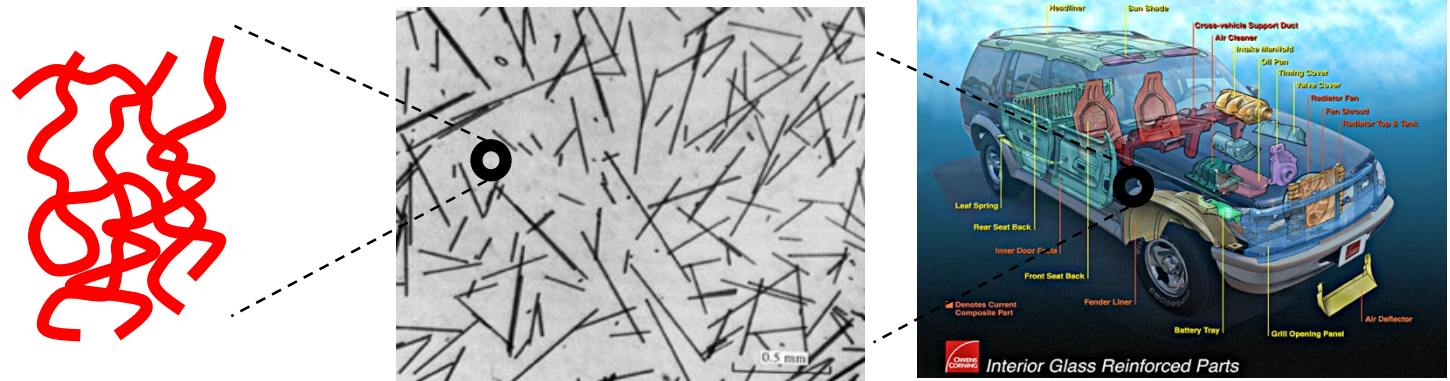
Matériaux composites,  
D. Gay, Hermes, 1997,2005

From bakelite to composite, design in new materials  
Bucquoy E. ed., Stichting Kunstboek, Gent,

Process modeling in Composites manufacturing, S. Advani,  
M. Sozer, Marcel Dekker

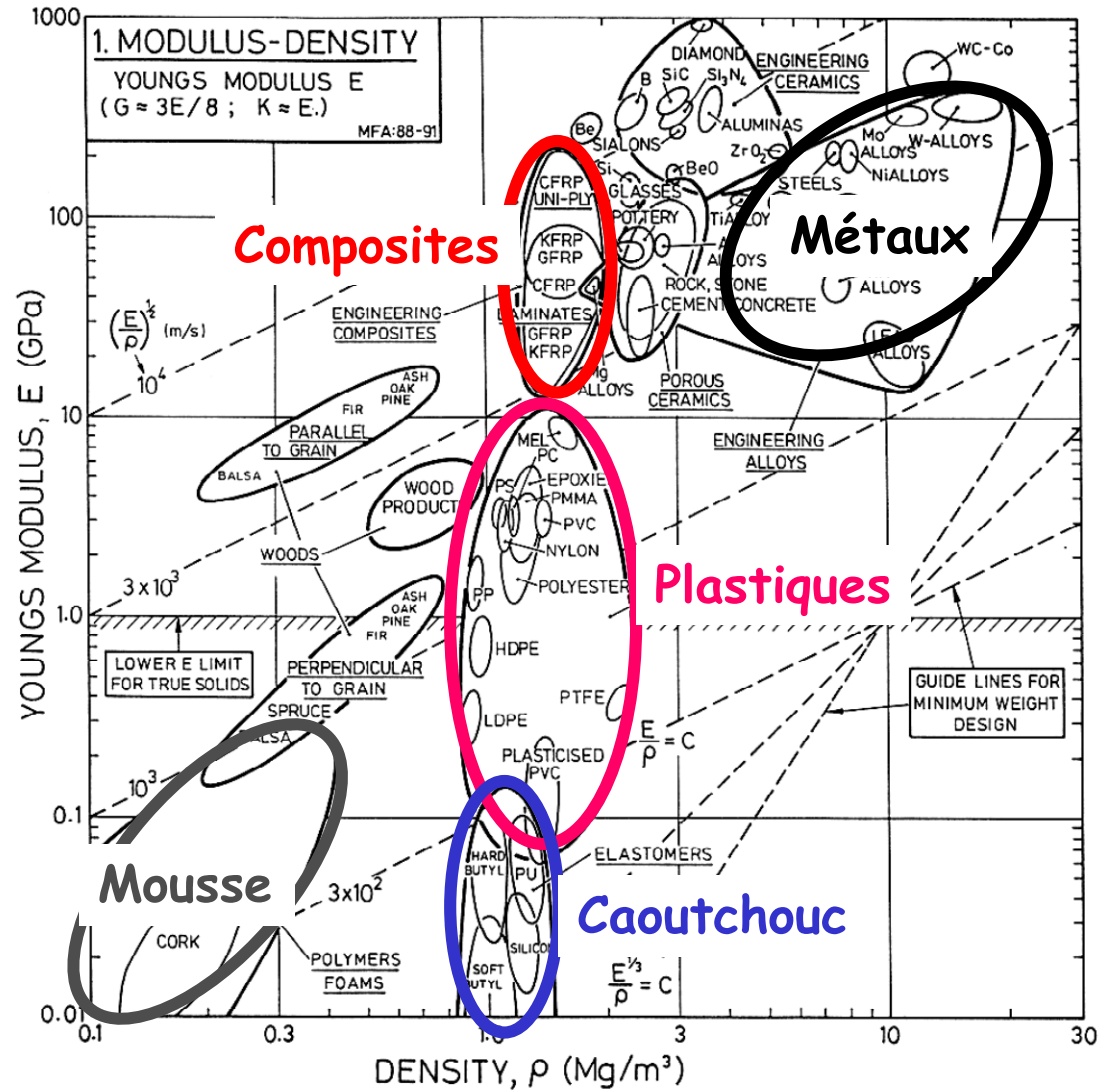
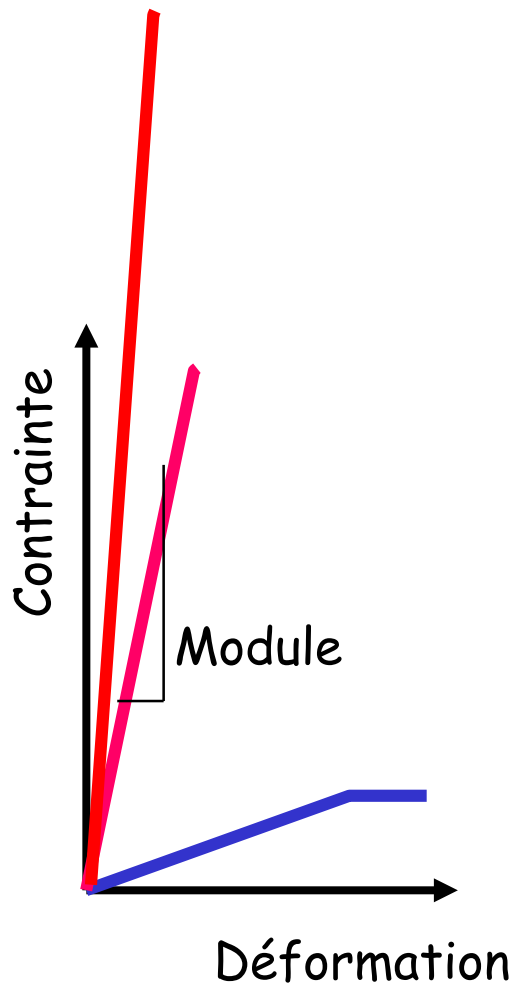
# Les polymères et leurs composites

- Introduction
- Applications
- Composants
- Mécanique



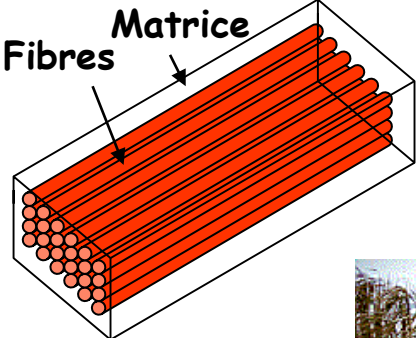
Matrice continue et renforts

# Propriétés: module - densité



M.F. Ashby, Materials Selection for Mechanical design, Pergamon Press

# Matériaux composites



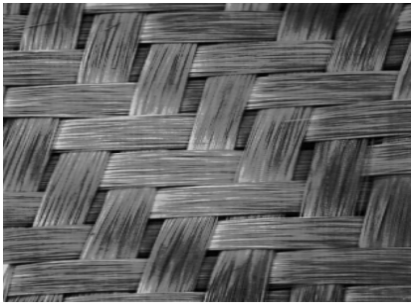
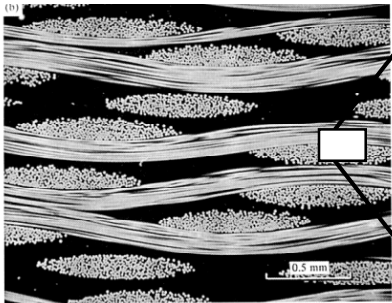
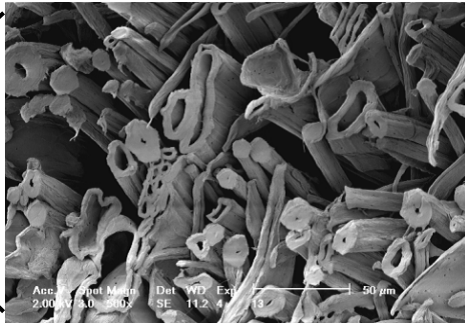
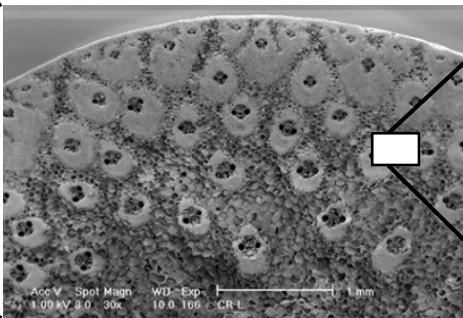
*bois*

*torchis*

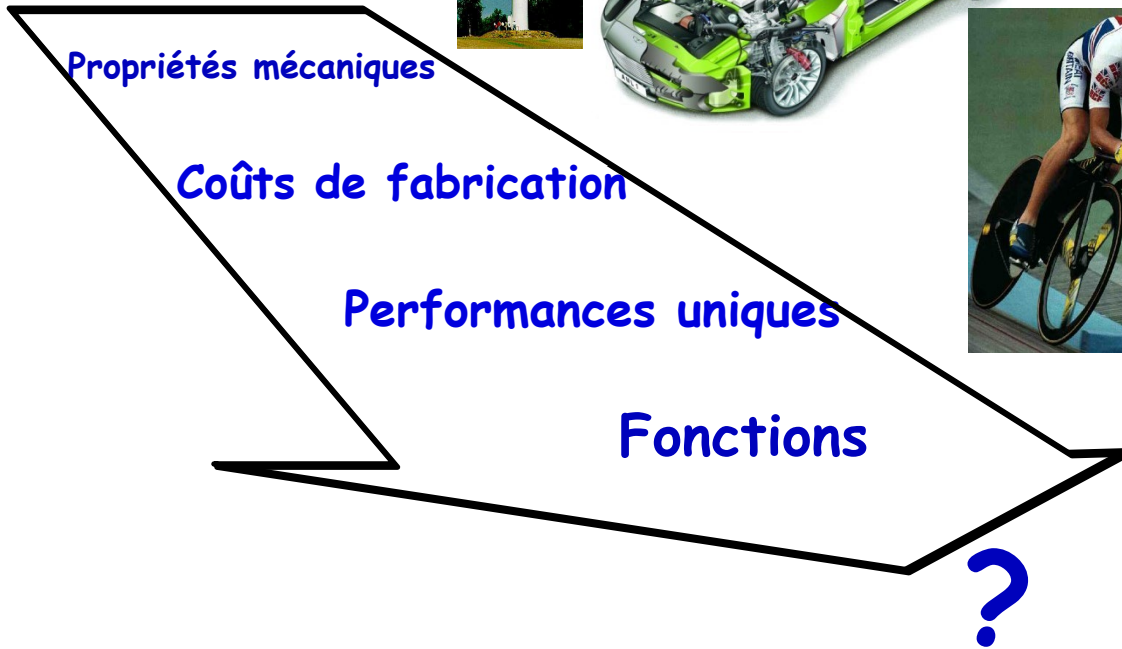
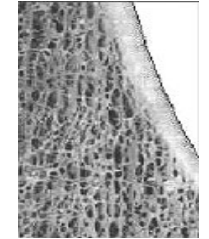
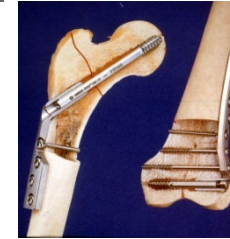
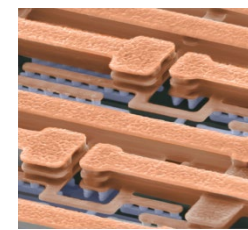
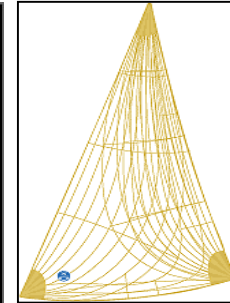
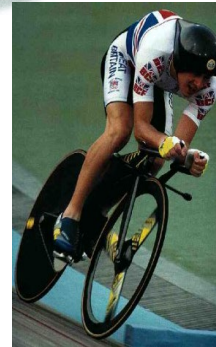
*tissus vivants*

*carapaces d'insectes*

*béton armé*

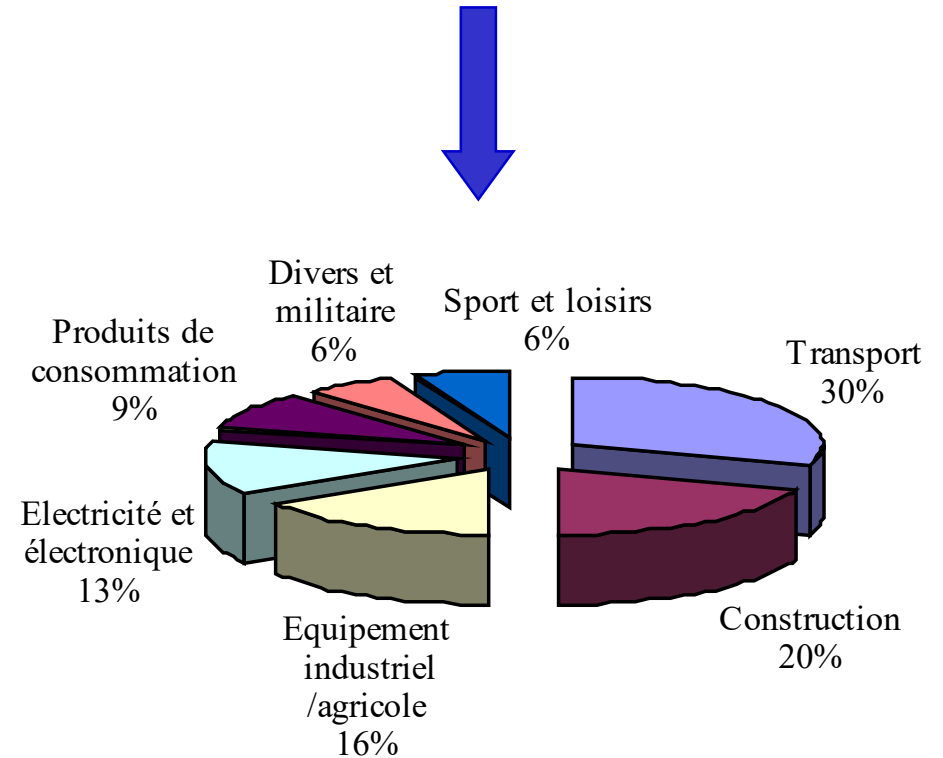
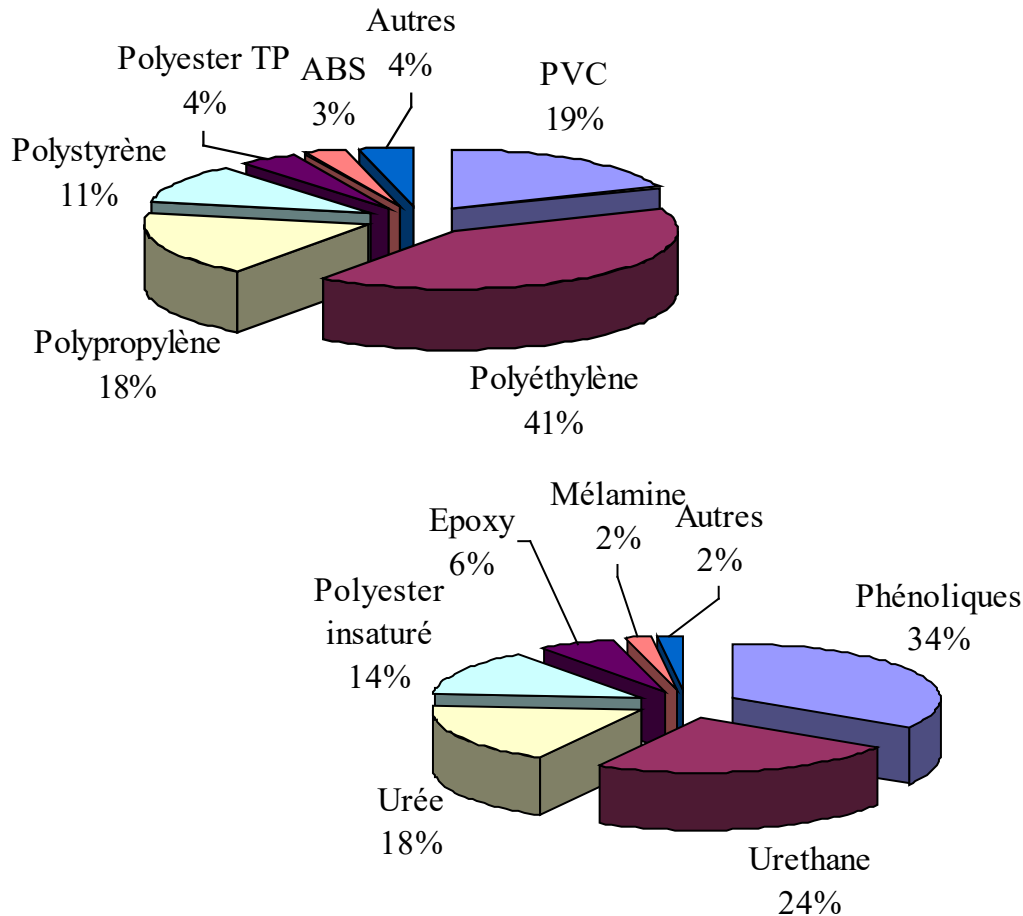


# Evolution des composites



# Polymères et composites organiques

Les polymères, .....dont  $5 \cdot 10^6$  t. pour les composites

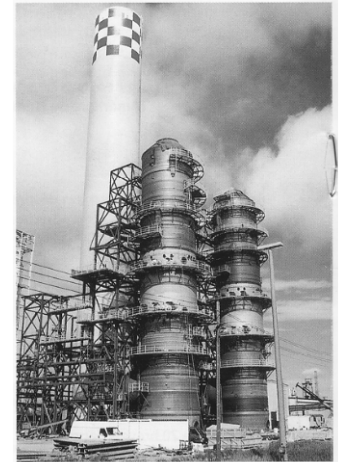


# Applications des composites



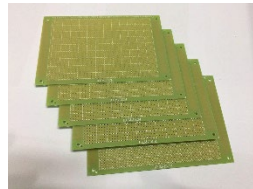
## Sports et loisirs

Raquette de tennis, skis, clubs de golf, perches pour le saut, arcs et flèches, casques, cannes à pêche



## Mécanique

Engrenages, boîtiers, corps de vérin, bras de robots, roues inertielles, éléments de métiers à tisser, tuyauterie, bouteilles sous pression, tubes de forage, pneus.....



## Construction civile

Piscines, panneaux de façades, profilés, mobilier, coffrages, éléments de ponts...

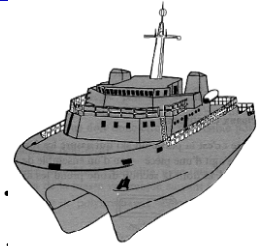


## Electricité, électronique

Isolants, supports de circuits imprimés, capots, antennes, radômes, chemins de cable, éoliennes....

# Applications pour le transport

Coques de bateaux, hovercrafts, voilier de compétition, mats,..



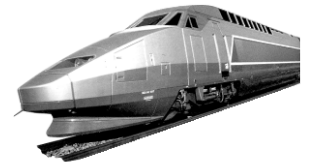
Transport maritime

Avions de tourisme et planeurs tout composite  
Pièces d'avions: bords d'attaque, volets, dérives  
Planchers, sièges, pales d'hélicoptère...

Transport aérien

Transport routier

Pièces de carrosseries, pare-chocs, calandres,  
ressorts de suspension, poutres de chassis,  
carters, sièges, citernes, caravanes, camions



Transport ferroviaire

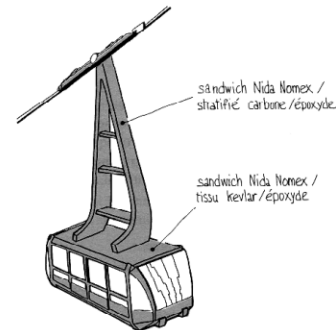
isothermes,  
Carrosserie de locomotives, wagon, sièges portes, gaines de ventilation

Transport spatial

Réservoirs, tuyères, corps de propulseurs

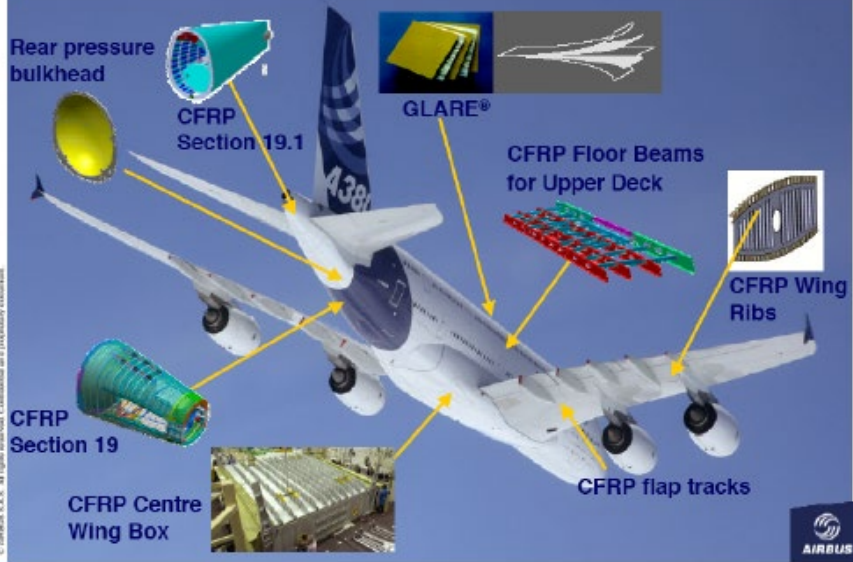
Transport filaire

Cabines de téléphériques



# Transport aérien

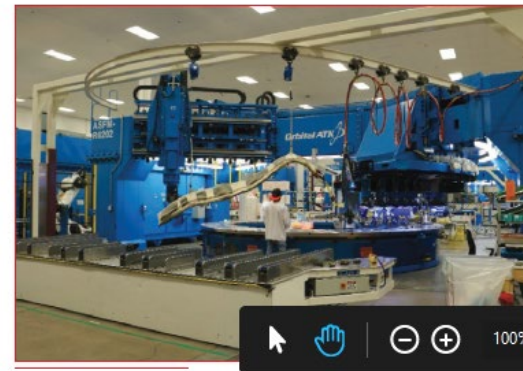
## A380 Composites major new applications



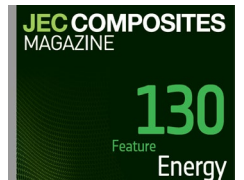
Airbus A350 XWB stringers and frames



Automated stiffener forming (ASF) for linear stringers



Automated stiffener forming for composite frames

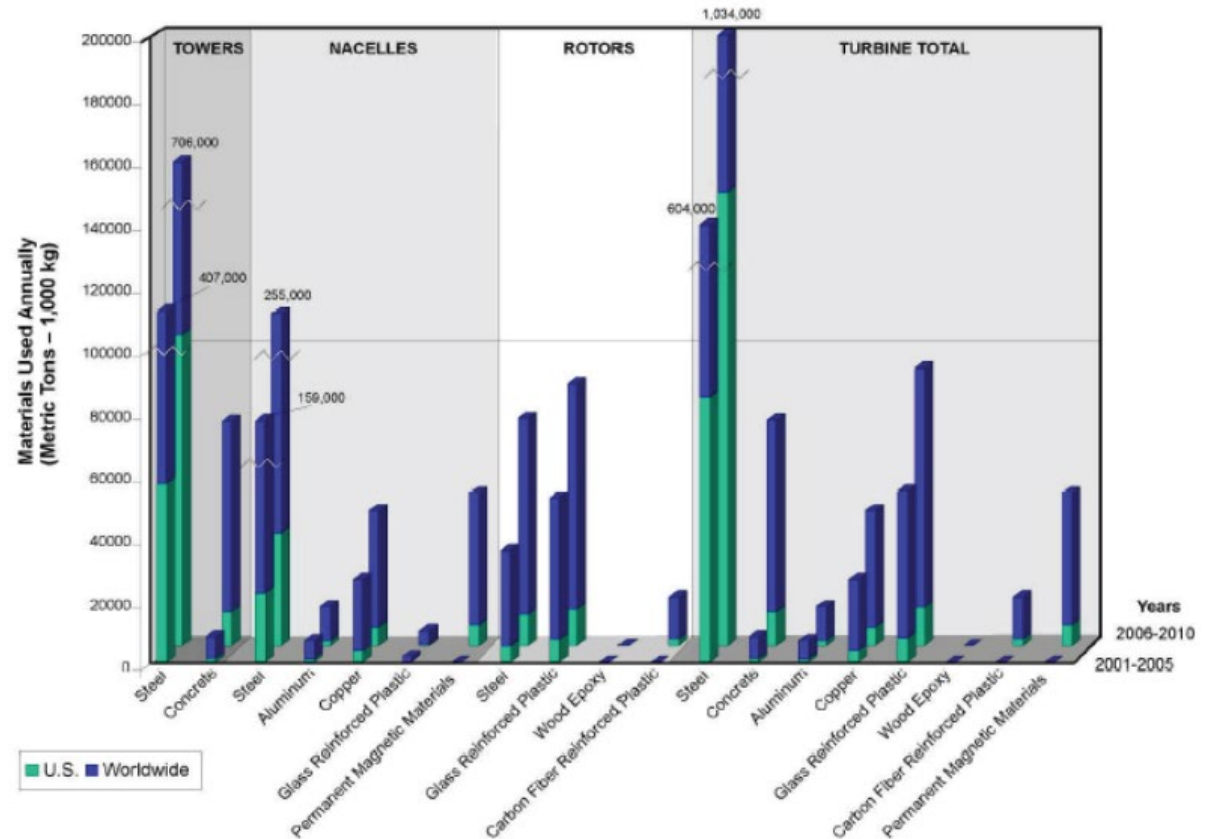


# Energie

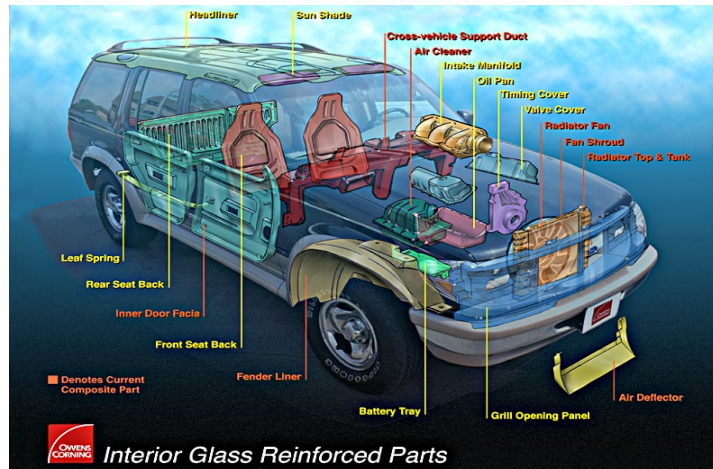


[www.rhoneole.ch](http://www.rhoneole.ch)

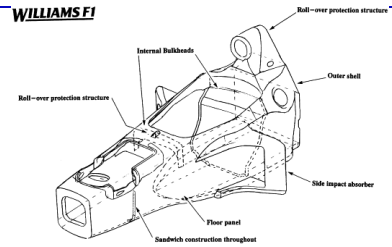
## Wind Turbine Materials Usage



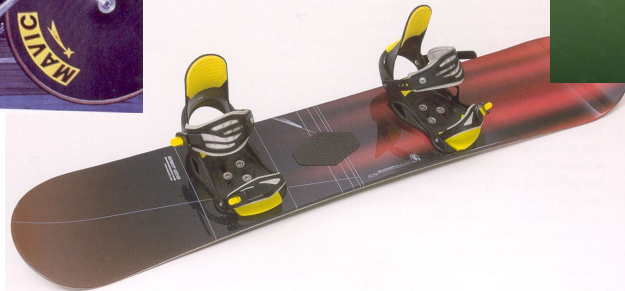
# Transport automobile



**WILLIAMS F1**



# Sport

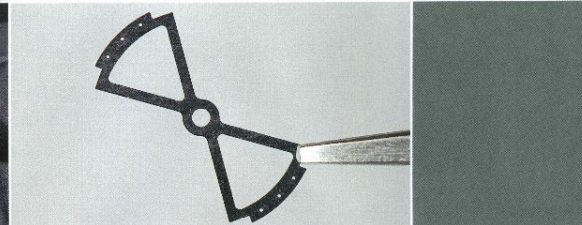
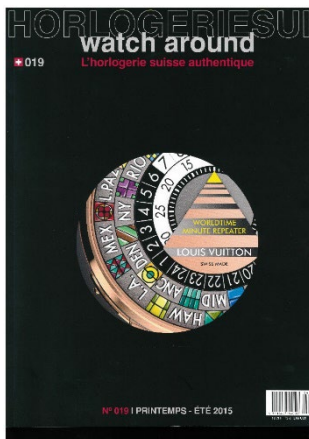


# Horlogerie



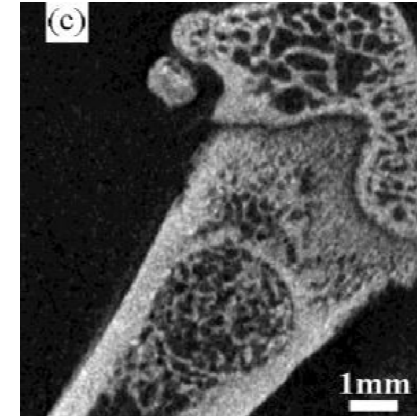
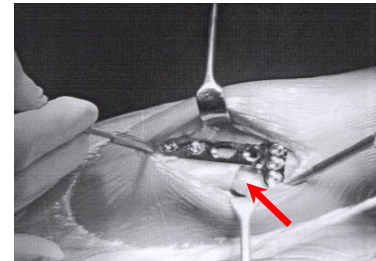
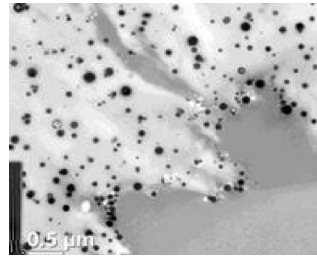
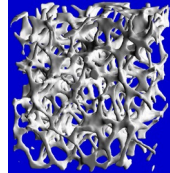
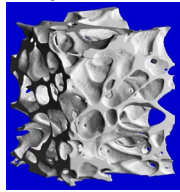
Oak Carbon

<http://www.audemarspiguet.com>

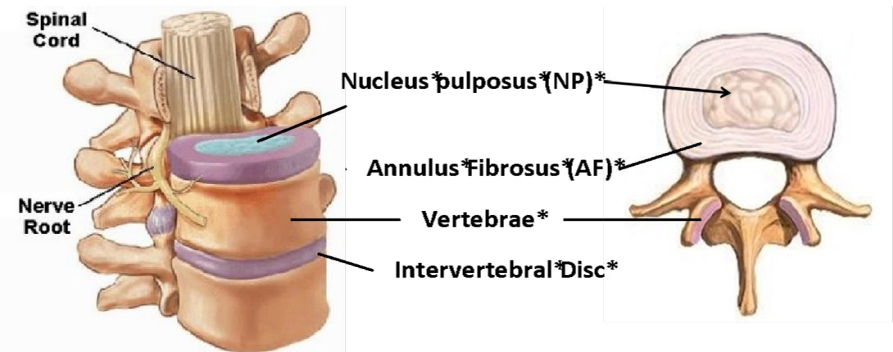
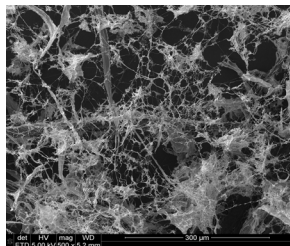


# Composites pour le biomédical

## Mousses composites biorésorbables

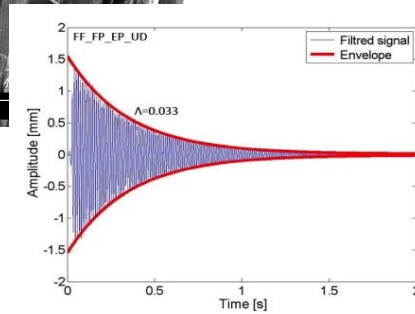
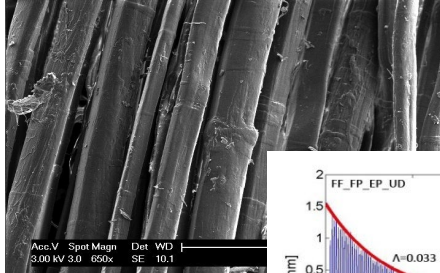


## Hydrogels composites



# Biocomposites naturels

## Composites à fibres naturelles



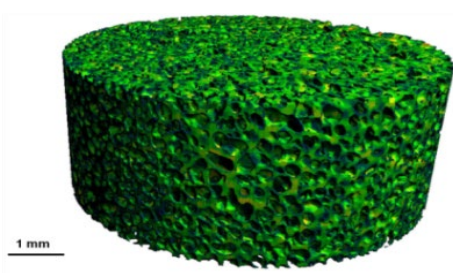
**Museeuw:** flax/carbon epoxy

**Artengo:**  
flax(5%)/  
carbon epoxy

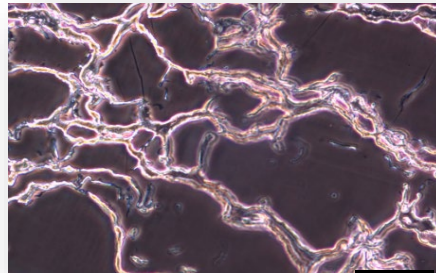


**Stockli**

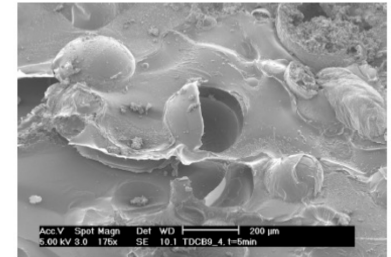
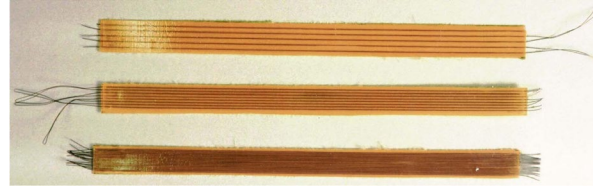
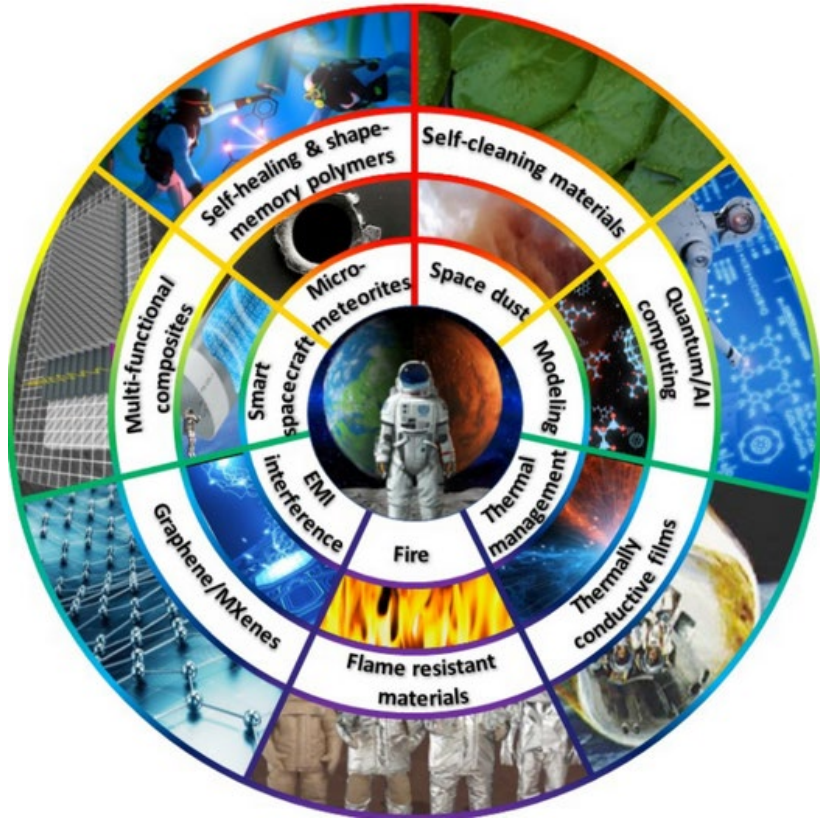
## Composites biodégradables



0 [mm] 0.186



# Smart Composites



Kirkby, 2005

Functionnal active fibres and/or particles  
EPFL-LPAC, Véronique Michaud



Head Intelligence skis

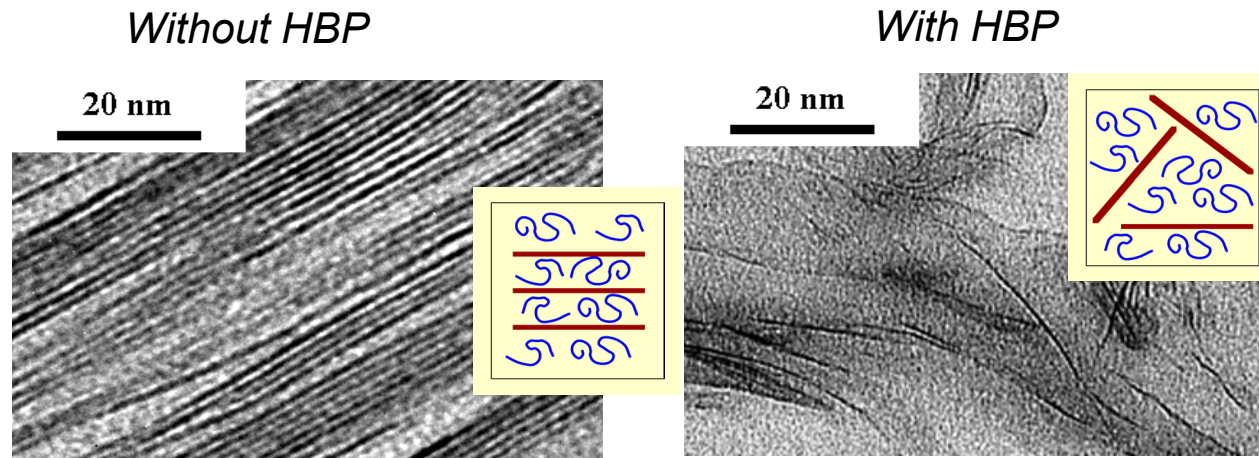


ADAPT project

Advanced Composites and Hybrid Materials (2023) 6:130  
<https://doi.org/10.1007/s42114-023-00678-5>

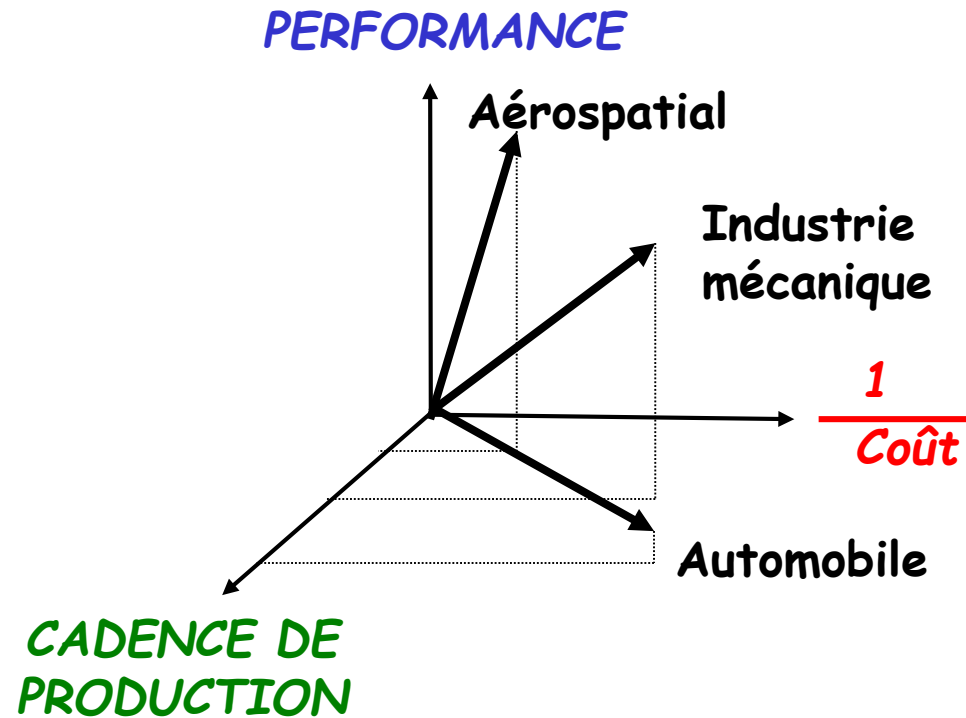
# Nanocomposites

## Nanocomposite structures



Christopher Plummer, LMOM-IMX

# Motivations



# Pourquoi utiliser des composites ?

**Personnalisation** des propriétés mécaniques et physiques

**Liberté de design** : par exemple, un CET  $\sim 0$ , anisotropie et morphing....

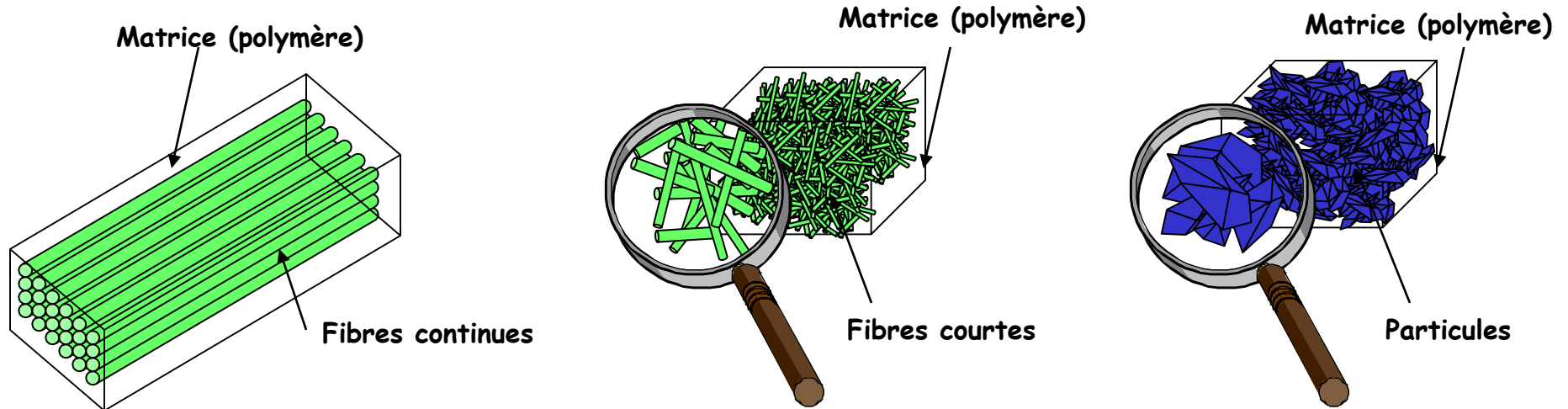
**Rigidités spécifiques élevées**, une réduction de poids tout en gardant la rigidité et la résistance, résistance à la fatigue, résistance à l'impact, résistance à la corrosion....

**Fabrication intégrée**

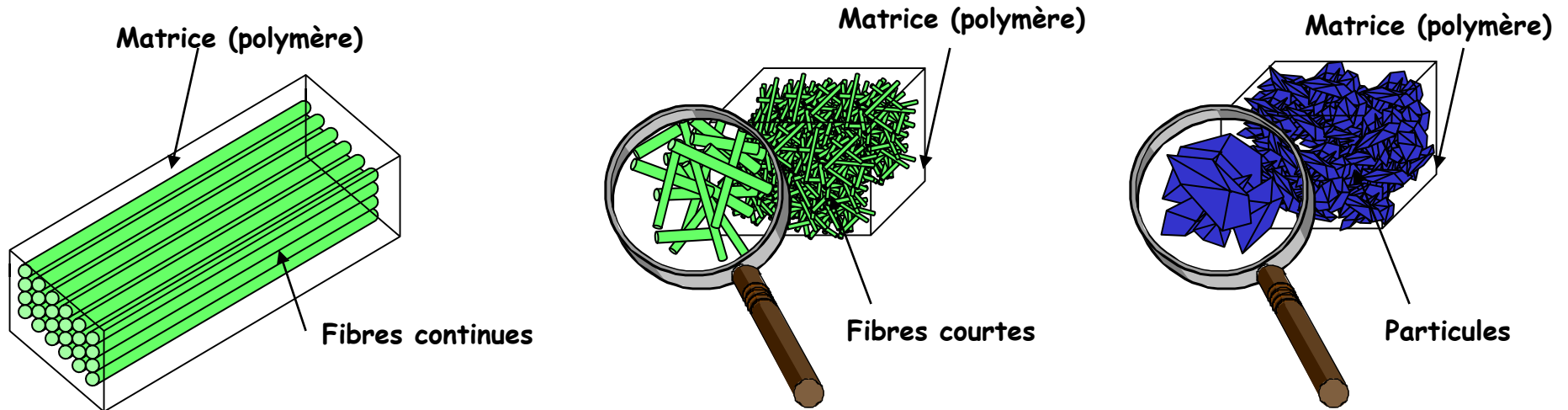
# Matériaux composites

Une combinaison et une synergie entre  
deux et plusieurs matériaux

Un matériau constitué d'une matrice continue contenant un renfort  
sous forme de fibres ou de particules.



# Matériaux composites

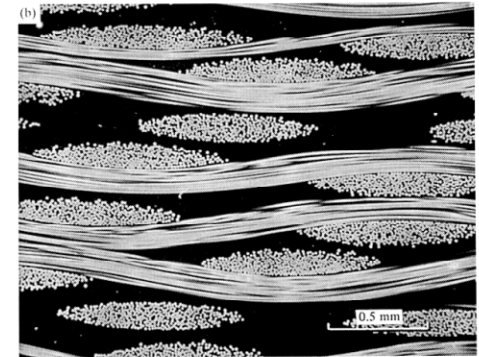
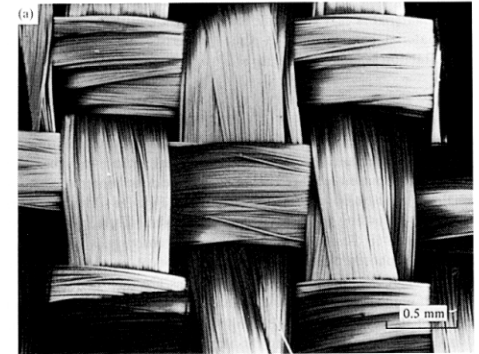
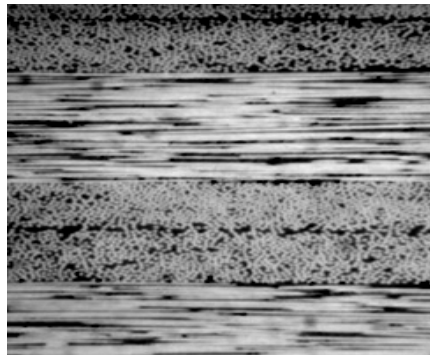
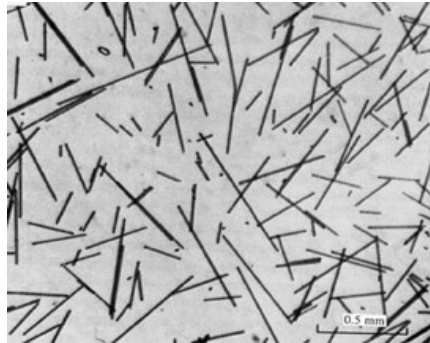
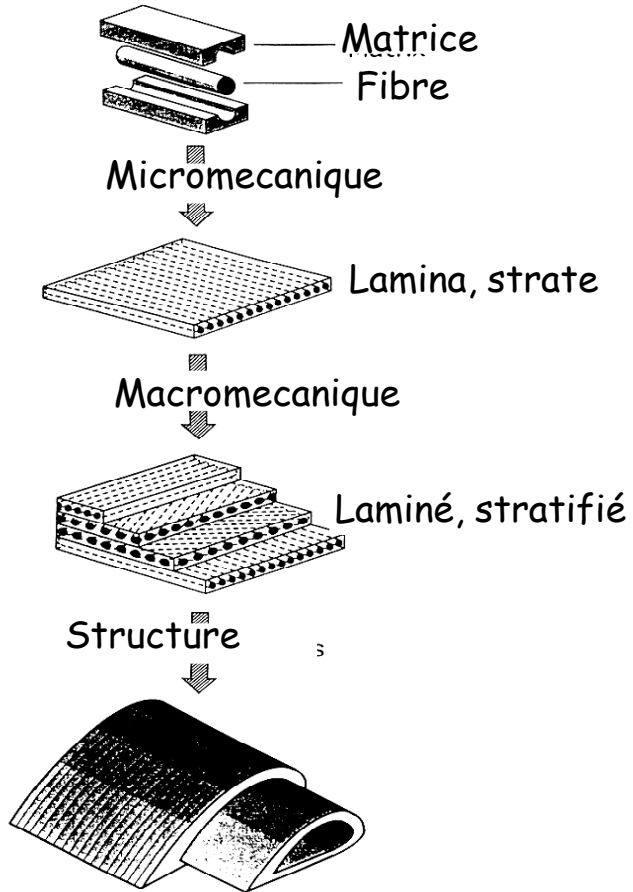


- Fibres orientées
- Composites unidirectionnels (UD)
- Thermodurcis, thermoplastiques
- Haute performance mécanique
- Anisotropie
- Aérospatiale, sport, réservoirs sous pression...

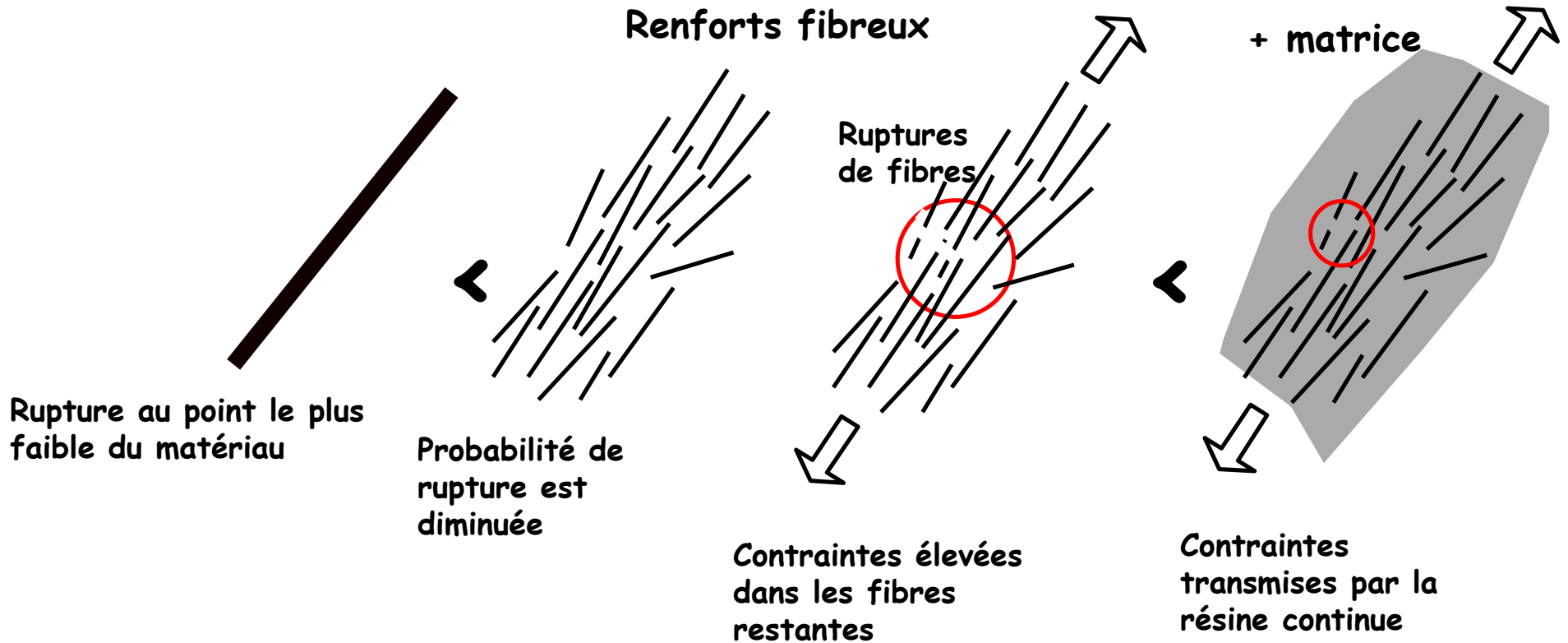
- Distribution de fibres courtes (< 3mm)
- Surtout des matrices thermoplastiques
- Isotropie
- Moulage par injection
- Mécanique, microtechnique, automobile....

- Particules (1-400 $\mu$ m), silice, argile...
- Thermodurcs and thermoplastiques
- Amélioration des propriétés
- Stabilité dimensionnelles
- Reduction de coût
- Moulage par injection, coulée
- Mécanique, microtechnique, dentisterie....

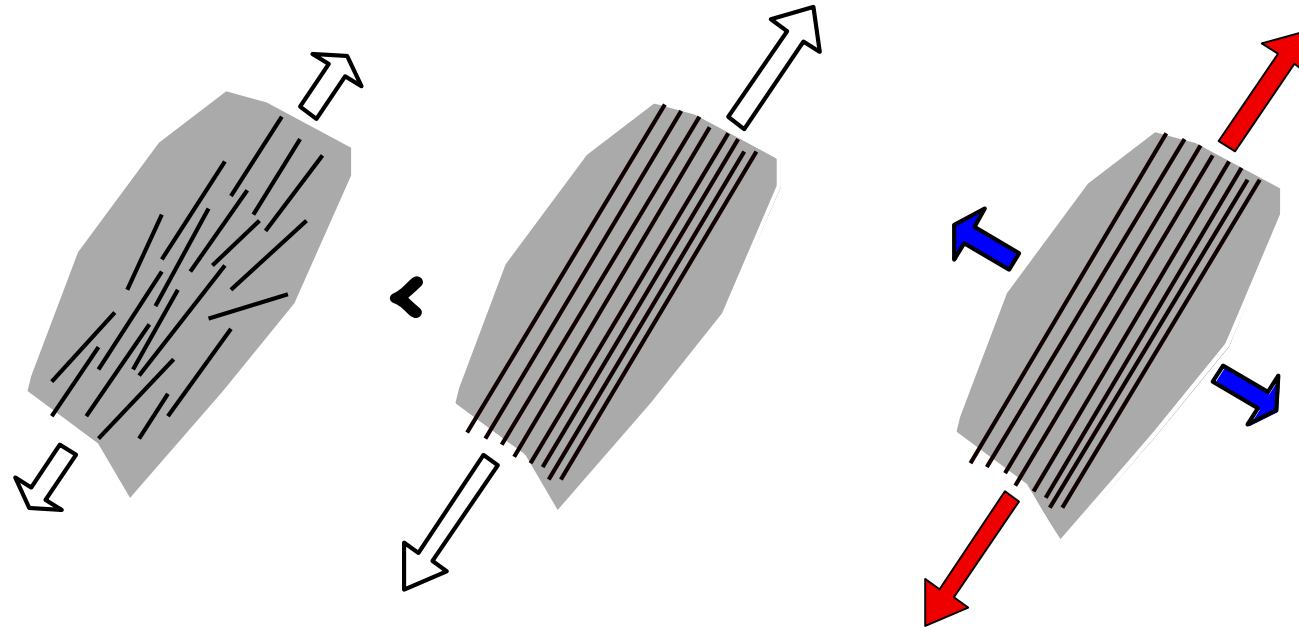
# Structure des composites



# Pourquoi des renforts ?

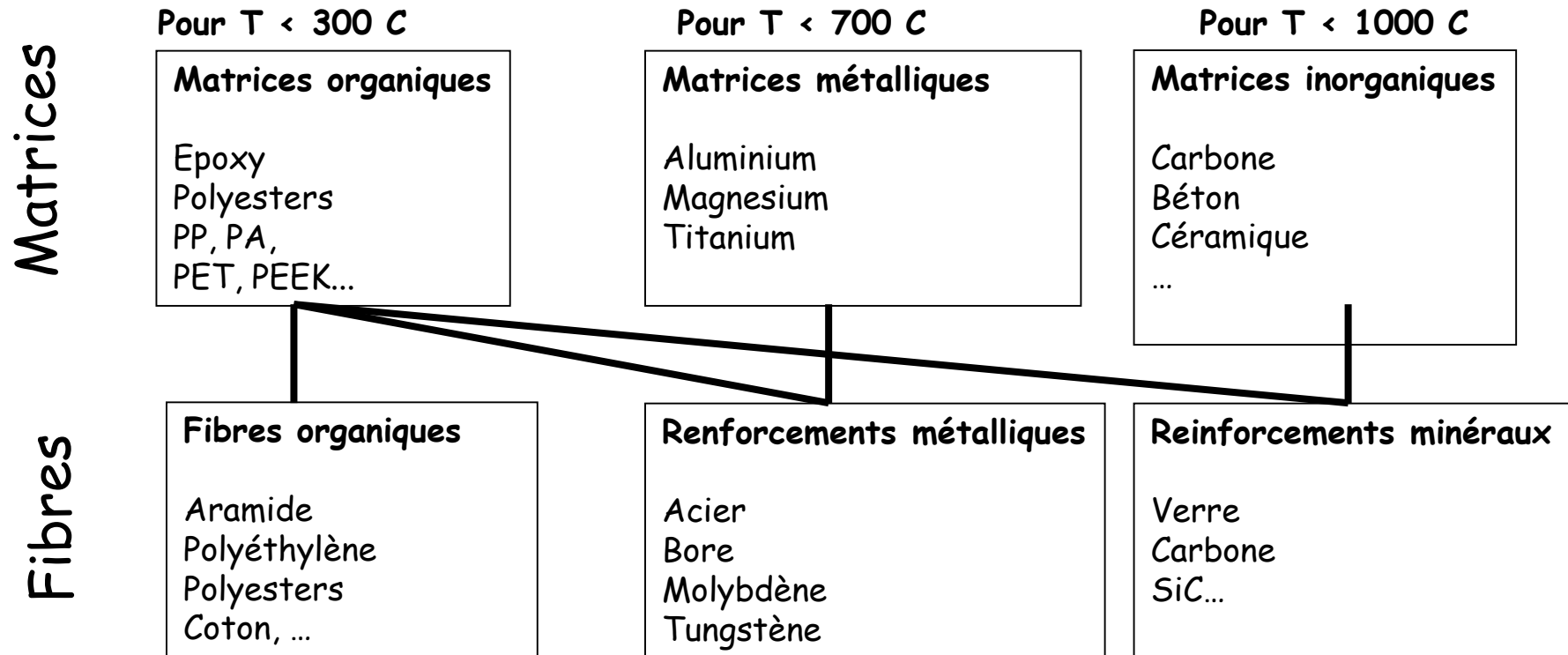


# Anisotropie



Renforts continus, orientés

# Renforts et matrices



# Les marchés

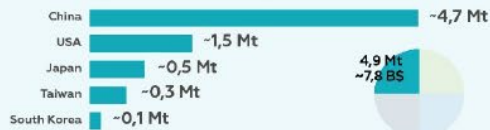
## Overview of the global composites' material market in 2019<sup>(1)</sup>

### Glass fibre

#### Top players



#### Top régions for production 2019



#### Top applications

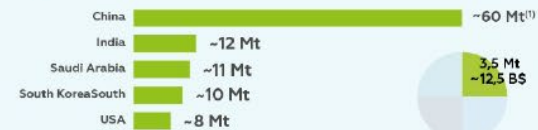


### Thermoset resin

#### Top players



#### Top régions for production 2019



#### Top applications



### Carbon fibre

#### Top players



#### Top régions for production 2019



#### Top applications



### Thermoplastic resin

#### Top players



#### Top régions for production 2019



#### Top applications



Note:  
 (1) Production of material for all applications, composites and other applications  
 Sources: Extin & Co interviews, analysis and estimates

# Applications des composites à fibres de carbone

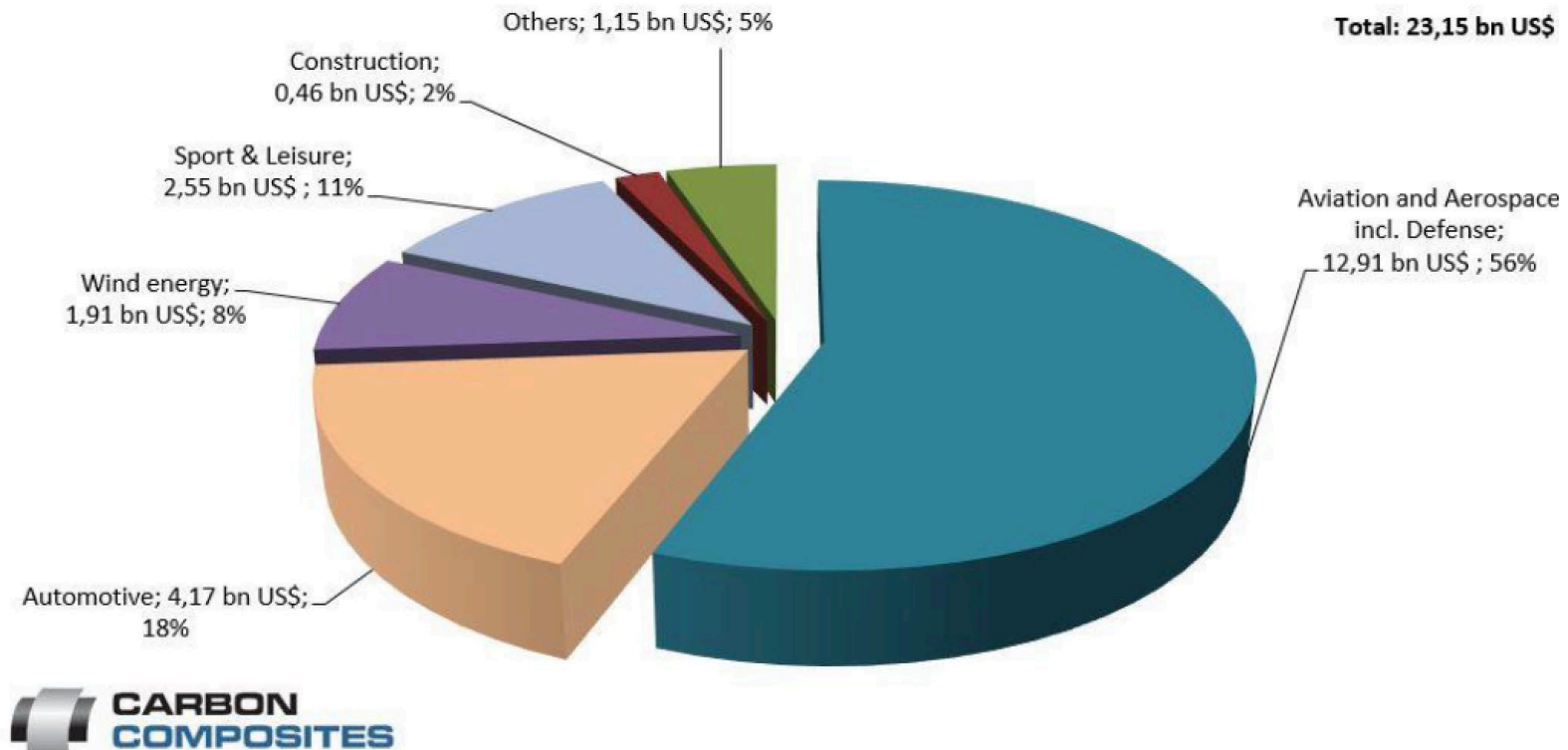


Figure 10: Global CC-Turnover in Thsd. Tons by application (11/2018).

Sources: CC Schweiz, Suschem report

# Les fibres de carbone

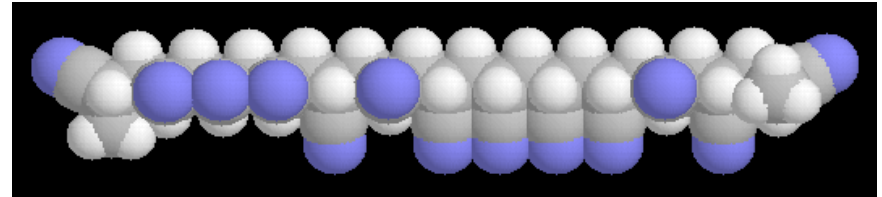
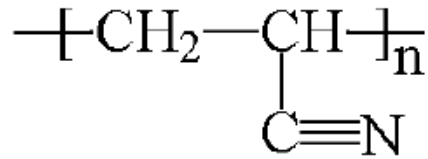
Historique: initialement à partir de résidus du pétrole (brai) pour des filaments de lampe...s' améliore dans les années 60 grâce à des traitements thermiques ou d'oxydation.

2 méthodes principales:

- A partir d'un polymère précurseur, le PAN (fibre acrylique)
- A partir du brai.

# Les fibres PAN : Fabrication

## Fibres à base de PAN

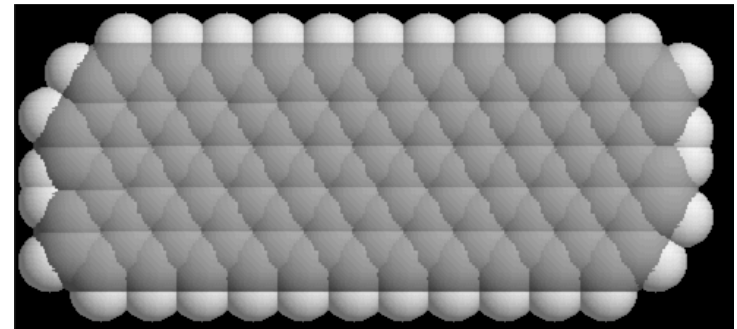
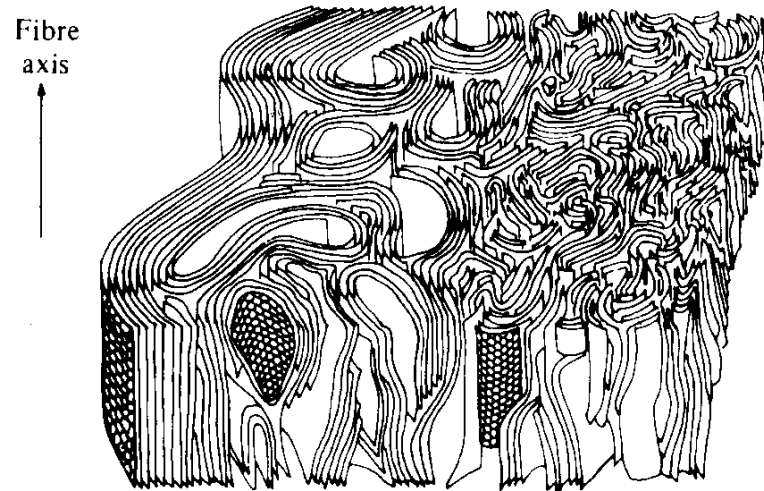


## Fabrication

- 1- filage et étirage du PAN
- 2- stabilisation 200 à 300°C dans l'air pendant 30 minutes
- 3- Carbonisation 1000 à 1600°C dans l'azote pour **High Strength HS**, 2500 à 2800° C pour **High Modulus HM** (sous tension)
- 4- Traitement de surface: oxidation anodique dans la soude...

# Structure

Les fibres de C obtenues par pyrolyse d'un précurseur polyacrylonitrile (PAN) possèdent des propriétés mécaniques exceptionnelles



Représentation schématique d'une fibre de C

# Propriétés

Propriétés des fibres base PAN:

HS:  $E = 200$  à  $400$  Gpa,

Résistance :  $3.6$  à  $4.6$  Gpa,

% élongation:  $1.4$ - $1.8$

HM:  $E = 600$ - $800$  Gpa,

Résistance :  $3.6$  à  $4$  Gpa,

%élongation:  $0.5$ - $0.8$

Module transverse: environ  $10$  Gpa

Coefficient d'Expansion thermique longitudinal:  $-0.3$  à  $-0.7 \cdot 10^{-6}/^{\circ} C$

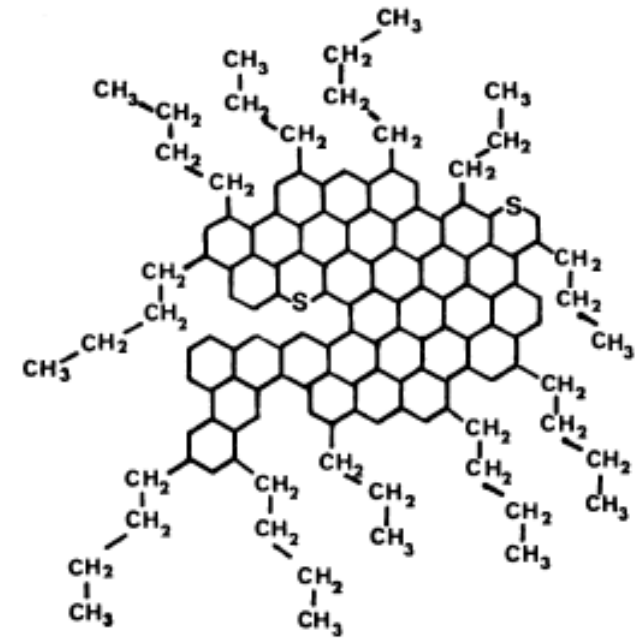
# Types et Propriétés

Table 2 Mechanical and other properties of types of CFs extracted from manufacturers' data sheets.

<i>Mfr.</i>	<i>Fiber type</i>	<i>Filament count</i>	<i>Filament diameter (μm)</i>	<i>Surface area (m<sup>2</sup> g<sup>-1</sup>)</i>	<i>Tensile strength (MPa)</i>	<i>Tensile modulus (GPa)</i>	<i>Tensile strain (%)</i>	<i>Density (g cm<sup>-3</sup>)</i>
Amoco [Thornel]	T-300	1k, 12k	7.0	0.45	3650	231	1.4	1.76
	T-40	12k	5.1	0.5	5650	290	1.8	1.81
	T650/42	6k, 12k	5.1	0.5	4620	290	1.6	1.78
Hexcel	T-50	3k, 6k	6.5	0.45	2900	390	0.7	1.81
	AS4	3k, 12k			3930	221	1.7	1.79
	IM4	12k			4138	276	1.5	1.73
	IM7	6k, 12k			5379	276	1.8	1.77
	UHM	3k, 12k			3447	441	0.8	1.87
Mitsubishi rayon [Pyrofil]	TR30	3k			3530	235	1.5	1.79
	TR50	12k			4900	235	2.1	1.80
	MR50k	12k			5490	294	1.8	1.80
	SR50	12k			4220	490	0.9	1.88
Sigrafil	C30		6.8		3000	230	1.4	1.78
	C35		7.0		3200	210	1.4	1.8
Tenax	HTA	1k, 24k	7.0		3950	238	1.5	1.77
	UTS	12k	7.0		4800	240	2.0	1.8
	IMS	6k, 24k	5.0		5500	290	1.9	1.8
	UMS	12k	4.7		4500	435	1.1	1.81
Toho rayon [Besfight]	HTA	3k, 12k	7.0		3920	235	1.7	1.77
	ST4	12K	7.0		4810	240	2.0	1.78
	IM600	12k, 24k	5.0		5790	285	2.0	1.80
	HM35	12k	6.7		3240	345	0.9	1.79
	TM40	12k	6.2		3430	390	0.9	1.85
	UM68	12k	4.1		3330	650	0.5	1.97
Toray [Torayca] * available from	T300*	1 – 12k	7.0		3530	230	1.5	1.76
	T300J*	3k, 12k	7.0		4210	230	1.8	1.78
	T700S	12k	7.0		4900	230	2.1	1.80
	T800H*	6k	5.0		5490	294	1.9	1.81
Soficar	T1000G	12k	5.0		6370	294	2.2	1.80
	M40J*	6k	5.0		4410	377	1.2	1.77
	M50J	6k	5.0		4120	475	0.8	1.88
	M60J	3k, 6k	5.0		3820	588	0.7	1.94
	X665	6k	5.0		3430	637	0.5	1.98
	M40*	6k, 12k	7.0		2740	392	0.7	1.81
	Zoltek [Panex]	Panex33	48k, 320k	7.4		3600	228	
	Panex30				1552	221		1.75

# Les fibres à base de brai

le brai forme des cristaux liquides si traité thermiquement, que l'on peut orienter par filage



**Natural  
Pitch**

Figure 5 A naturally occurring pitch with a large aromatic core and long solubilizing alkyl groups, MW = 3200. The thermally unstable alkyl groups cleave off at spinning temperatures to cause unsatisfactory bubbling.

# Fabrication

## Fibres à base de brai:

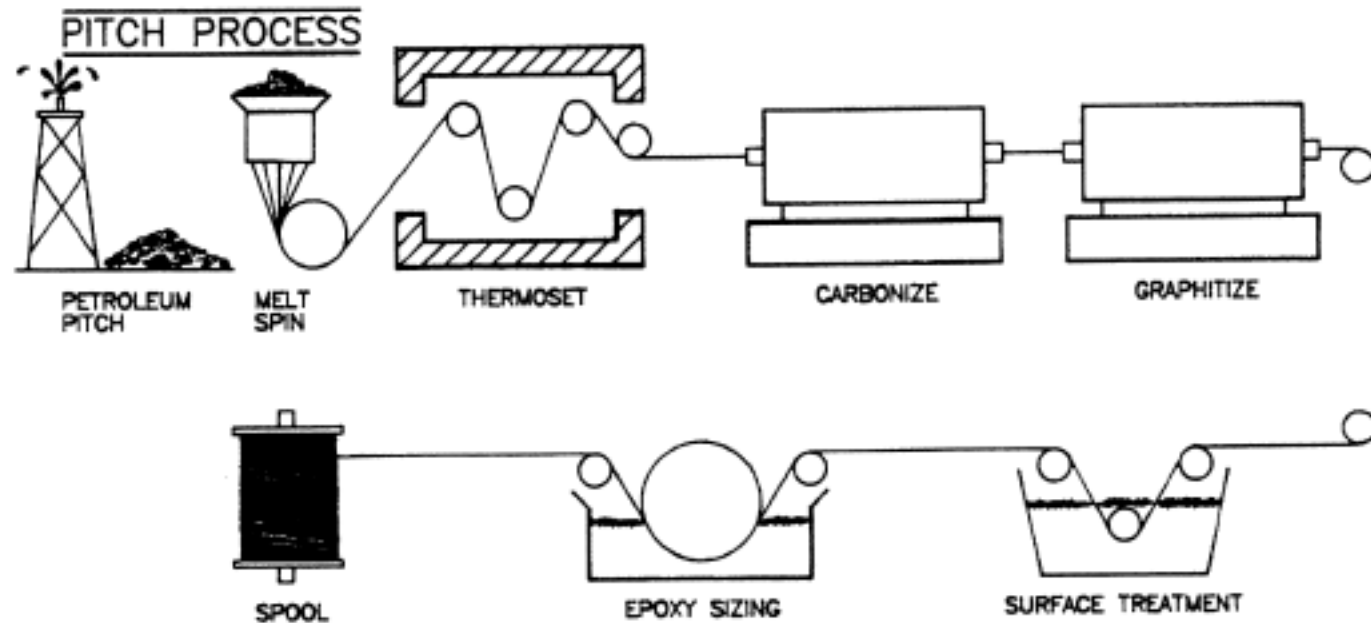


Figure 13 Pitch precursor carbon fiber process. Pitch is melt spun into fibers that are thermoset and then carbonized to carbon fibers. The modulus of mesophase pitch precursor carbon fibers is increased by subsequently heating to a high temperature, and the surface of the fiber is etched for improved bonding with a resin matrix (reproduced by permission of Fiber Producer, Greenville, from Fiber Producer, 1979, pp. 16–21).

# Types et propriétés

Fibres à base de brai:  
Modules: 160 à 930 Gpa,  
Résistance : 1.4 à 3 Gpa  
Fibres très chères et  
donc moins utilisées.

Table 3 Manufacturer's data on mechanical properties.

	<i>Tensile modulus</i> (GPa)	<i>Tensile strength</i> (GPa)	<i>Density</i> (g cm <sup>-3</sup> )
BP-Amoco			
P-25	160	1.4	1.90
P-55S	380	1.9	2.00
P-75S	520	2.1	2.00
P-100	760	2.4	2.16
P-120	830	2.4	2.17
K-800x	930	2.9	2.18
K-1100	930	3.1	2.20
Mitsubishi Kasei			
K133	440	2.4	2.08
K135	540	2.6	2.10
K137	640	2.7	2.11
K139	740	2.8	2.12
K321	180	2.0	1.90
Nippon graphite fiber			
YS-50A	520	3.8	2.09
YS-60	590	3.5	2.12
YS-70A	720	3.6	2.14
YS-80	785	3.5	2.15
Isotropic pitch Kureha			
T101F	33.0	0.80	1.81
T201F	33.0	0.70	1.57

# Les fibres de verre

Propriétés des filaments:

- Taille, 10 à 20  $\mu\text{m}$  de diamètre
- Module 70 GPa, jusqu' à 90 GPa
- Résistance à rupture: 3.95 GPa si fraîche, moins dans la pratique 1 à 2 GPa.
- Points négatifs: Résistance aux acides, abrasion, corrosion sous contrainte dans l'eau.
- Coût: quelques CHF/kg, jusqu'à beaucoup plus pour le Quartzel.

# Fabrication

• FABRICATION

COMPOSITION DU VERRE



PRODUITS DE CARRIÈRE

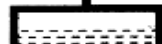
ÉLABORATION



FOUR

VERRE EN FUSION

FIBRAGE



FILIÈRE

ENSIMAGE

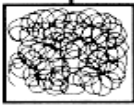


FILAMENTS  
ø 5 à 24 µm

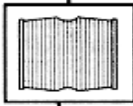
FIL DE BASE  
Masse linéique  
2,8 à 4800 tex



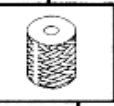
Fils coupés



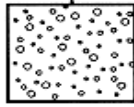
Mats fils continus



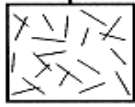
Gâteau



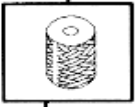
Roving



Fibre broyée



Fils coupés



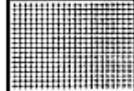
Roving



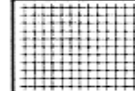
Fil textile



Mats fils coupés



Tissu fil textile



Tissu roving

# Compositions

Table 1 Composition ranges for the oxides used in specific commercial glass fibers.

Oxide	A-Glass (%)	C-Glass (%)	D-Glass (%)	E-Glass (%)	ECR-Glass (%)	AR-Glass (%)	R-Glass (%)	S-2-Glass (%)	No boron E-Glass (%)
SiO <sub>2</sub>	63–72	64–68	72–75	52–56	54–62	55–75	55–65	64–66	52–62
Al <sub>2</sub> O <sub>3</sub>	0–6	3–5	0–1	12–16	9–15	0–5	15–30	24–25	12–16
B <sub>2</sub> O <sub>3</sub>	0–6	4–6	21–24	5–10		0–8			
CaO	6–10	11–15	0–1	16–25	17–25	1–10	9–25	0–0.1	16–25
MgO	0–4	2–4		0–5	0–4		3–8	9.5–10	0–5
ZnO					2–5				
BaO		0–1							
Li <sub>2</sub> O						0–1.5			
Na <sub>2</sub> O + K <sub>2</sub> O	14–16	7–10	0–4	0–2	0–2	11–21	0–1	0–0.2	0–2
TiO <sub>2</sub>	0–0.6			0–1.5	0–4	0–12			0–1.5
ZrO <sub>2</sub>						1–18			
Fe <sub>2</sub> O <sub>3</sub>	0–0.5	0–0.8	0–0.3	0–0.8	0–0.8	0–5		0–0.1	0–0.8
F <sub>2</sub>	0–0.4			0–1		0–5	0–0.3		0–1.0

Source: Hartman *et al.*, 1996.

# Propriétés

- E-Glass:** Good Electrical properties  
But poor chemical resistance against acids  
Low cost: ~ 2,5 / 3 CHF/Kg
- C-Glass:** Better resistance to Chemical corrosion  
Veil of C-Glass  Element of homogenization  
 Good quality of surface
- D-Glass:** High Dielectric performances ( $\varepsilon = 3.85$  à 1 MHz)  
High cost : 40 x E-Glass / Mechanical performances lower than E-Glass
- R-Glass:** High mechanical Resistance ( modulus 86GPa)  
Cost: 10 x E-Glass / Good resistance to chemical corrosion (slightly < C-Glass)
- AR-Glass:** Alkali-Resistant  
Used in building -> Good chemical resistance against alkalies ( and also acids)  
But hydrophilic

# Ensimage

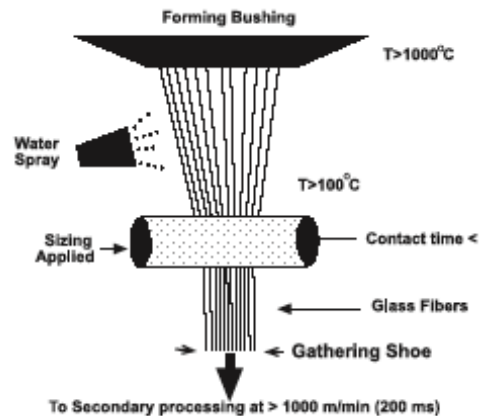
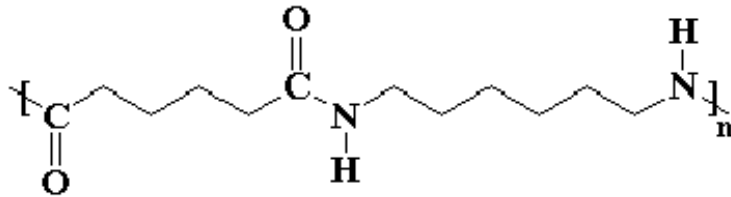


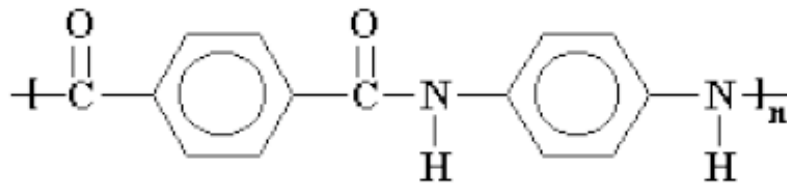
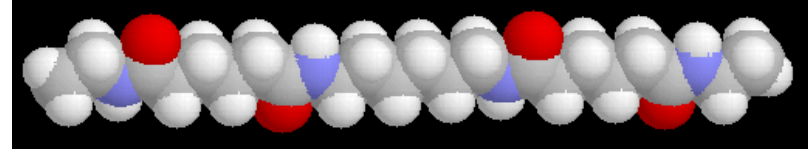
Table 8 Glass fiber sizing ingredients and functions.

<i>Ingredient</i>	<i>Function</i>	<i>Typical chemistry</i>
Film formers	Compatibilize with matrix, protect fibers, provide strand integrity	PVAc, epoxies, polyesters, polyurethanes, polyolefins, etc.
Lubricants	Protect fibers, improve forming efficiency	Imidazolines, pentamine stearates, hydrocarbon waxes, polyethylene glycols, mineral oil/amide esters, etc.
Coupling agents	Reduce aqueous stress corrosion, bonding between glass and resin	Organosilanes, chromates, titanates, and zirconates
Antistats	Reduce static charging via moisture adsorption	Quaternary ammonium compounds, halide salts
Nucleating agents	Increase number of spherulites in semicrystalline matrices	Maleated polypropylene
Surfactants	Emulsify resins, antifoam, adjust viscosity	Polyoxyethylene nonylphenyl ether, glycol ethers, EO/PO
Acids, bases	pH adjustment	Acetic acid, ammonium hydroxide

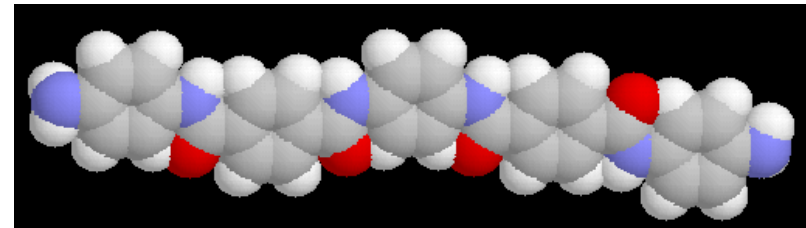
# Les fibres aramides



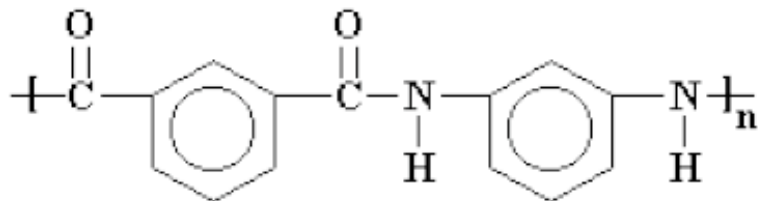
Structure chimique du PA 6.6



Structure chimique du Kevlar®



Le Kevlar® est un PA aromatique découvert en 1972 par DuPont  
Il est hautement cristallin et insoluble. Il fond à plus de 500°C



Structure chimique du Nomex®

Le Nomex® diffère du Kevlar® par l'existence des groupes  
meta-phénylène à la place des groupes para-phénylène

# Fabrication

- extrusion et filage du polymère en solution
- traitement thermique pour augmenter le degré de cristallinité et l'orientation

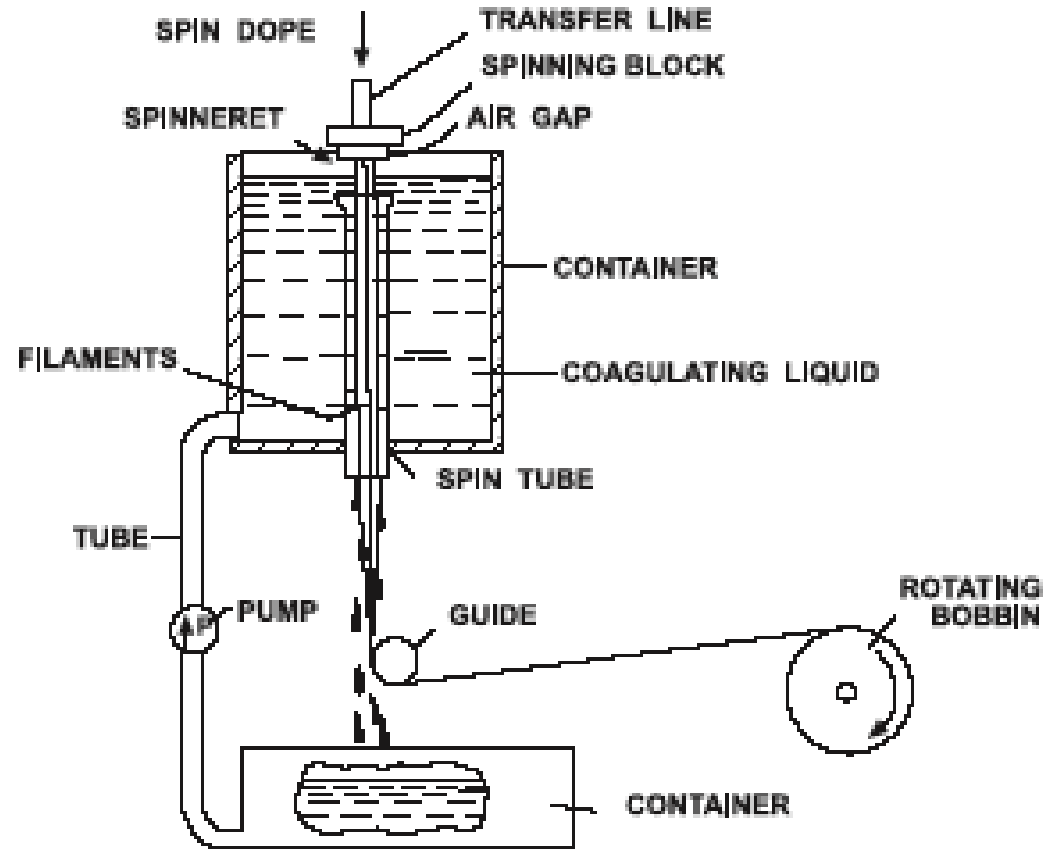


Figure 8 Dry-jet wet spinning process (Blades, 1973).

# Propriétés

Propriétés: Module 60 à 125 GPa

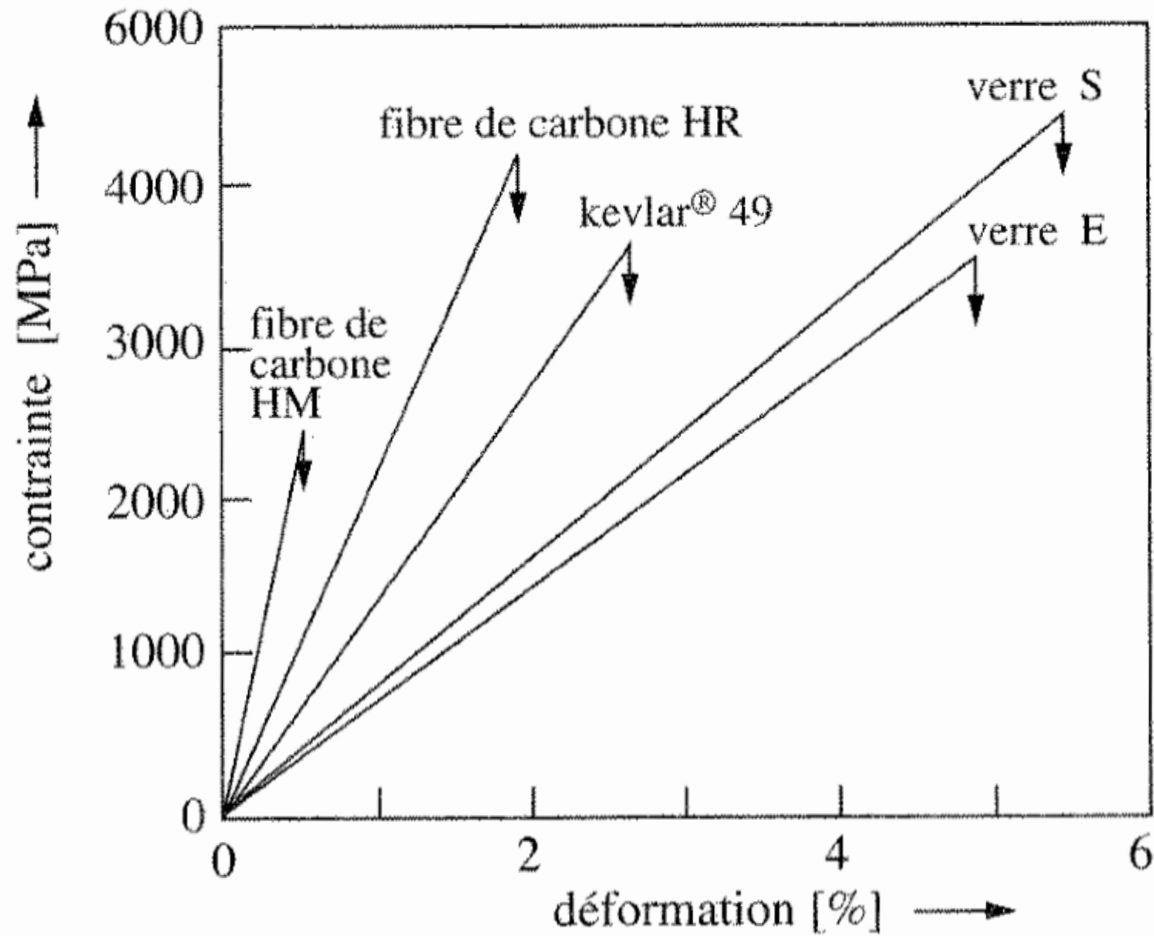
- Résistance: 2.7 à 3 GPa

- élongation: 2.5 à 3.5 %

-Problèmes: Résistance aux UV, compression.

Product type	<i>Kevlar</i>	<i>Kevlar</i>	<i>Kevlar</i> 49	<i>Kevlar</i> 68	<i>Kevlar</i> 119	<i>Kevlar</i> 129	<i>Kevlar</i> KM2
Denier per filament	1.5, 2.25	1.5, 2.25	1.5	2.25	1.5, 2.25	1.5	1.5
Filament diameter (mm)	0.012, 0.015	0.012, 0.015	0.012	0.012	0.012, 0.015	0.012	0.012
Density (g cm <sup>-3</sup> )	1.44	1.44	1.45	1.44	1.44	1.45	1.44
Tenacity (g den <sup>-1</sup> )	23	23	23	23.7	24	26.5	26
(GPa)	2.9	2.9	2.9	3.0	3.1	3.4	3.3
Elongation (%)	3.6	3.6	2.8	3.3	4.4	3.3	4.2
Tensile modulus (g den <sup>-1</sup> )	550	550	950	780	430	780	500
(GPa)	70	70	135	99	55	99	64
Moisture regain (%)	5-7	5-7	3-4	4-6	5-7	4-6	5-7

# Comparaison carbone-verre-aramide



# Propriétés des fibres polymères

*Table 1*  
Properties of some important synthetic fibers.

Material (fiber)	Tensile modulus (GPa)	Tensile strength (GPa)	Compressive strength (GPa)	Density (gcm <sup>-3</sup> )
Steel	200	2.8		7.8
Al alloy	71	0.6		2.7
Ti alloy	106	1.2		4.5
Alumina	350–380	1.7	6.9	3.9
Boron	415	3.5	5.9	2.5–2.6
SiC	200	2.8	3.1	2.8
S-glass	90	4.5	> 1.1	2.46
Carbon P100 (pitch-based)	725	2.2	0.48	2.15
Carbon M60J (PAN-based)	585	3.8	1.67	1.94
Kevlar 49	125	3.5	0.39–0.48	1.45
Kevlar 149	185	3.4	0.32–0.46	1.47
PBZT	325	4.1	0.26–0.41	1.58
PBZO	360	5.7	0.2–0.4	1.58
Spectra 1000	172	3.0	0.17	1.0
Vectran	65	2.9		1.4
Technora	70	3.0		1.39
Nylon	6	1.0	0.1	1.14
Textile PET	12	1.2	0.09	1.39

# Progression des fibres synthétiques

Fibre Type & Initial producer	Repeat Unit in the Macromolecule	Maximum Elastic Modulus (GPa)	Melting pt. or decomp. temp. °C
Polyamide 6 [Nylon 6] I.G.Farben	$\left[ \text{NH}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CO} \right]_n$	4	230
Polyamide 6/6 [Nylon 6.6] Du Pont	$\left[ \text{NH}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{NH}-\text{CO}-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{CO} \right]_n$	~5	260
Polyethylene terephthalate [Polyester] ICI	$\left[ \text{O}-\text{CO}-\text{C}_6\text{H}_4-\text{CO}-\text{O}-\text{CH}_2-\text{CH}_2 \right]_n$	~15	260
Poly(m-phenylenediamine-isophthalamide) Nomex Du Pont	$\left[ \text{NH}-\text{C}_6\text{H}_3(\text{NH}-\text{CO})-\text{CO} \right]_n$	17	400
Poly-paraphenylene/3,4-diphenylether terephthalamide [Technora] Teijin	$\left[ \text{NH}-\text{C}_6\text{H}_4-\text{NH}-\text{CO}-\text{C}_6\text{H}_4-\text{CO} \right]_m \left[ \text{O}-\text{C}_6\text{H}_4-\text{O}-\text{C}_6\text{H}_3(\text{NH}-\text{CO})-\text{CO} \right]_n$	70	500
Poly(p-phenylene terephthalamide) [Kevlar] Du Pont	$\left[ \text{NH}-\text{C}_6\text{H}_4-\text{NH}-\text{CO}-\text{C}_6\text{H}_4-\text{CO} \right]_n$	135	550
Poly(p-phenylene benzobisoxazole) PBO [Zylon] Toyobo	$\left[ \text{C}_6\text{H}_4-\text{O}-\text{N} \begin{array}{c} \diagup \diagdown \\ \diagdown \diagup \end{array} \text{N} \begin{array}{c} \diagup \diagdown \\ \diagdown \diagup \end{array} \text{C}_6\text{H}_4 \right]_n$	280	650
Poly{2,6-dimidazo[4,5-b:4'.5-e]pyridinylene-1,4(2,5-dihydroxy)phenylene} (PIPD) M5 AKZO	$\left[ \text{NH} \begin{array}{c} \diagup \diagdown \\ \diagdown \diagup \end{array} \text{N} \begin{array}{c} \diagup \diagdown \\ \diagdown \diagup \end{array} \text{NH} \begin{array}{c} \diagup \diagdown \\ \diagdown \diagup \end{array} \text{C}_6\text{H}_2(\text{OH})_2 \right]_n$	330	650

Accroissement de la rigidité des unités macromoléculaires

# D' autres fibres...

## UHMW-PE

(Ultra High Molecular Weight PE) Modulus: 85-98 Gpa,  $\sigma_{\max}=2.5-3.1$  GPa

Spectra® } melting point at  
Dyneema® } 150° C

## Exotic Organic Fibers

Zylon® [PBO (poly(p-phenylene-2,6-benzobisoxazole))]

Vectran® [LCP (Liquid Crystal Polymer)]

And other fibers ?

Dyneema  
Orientation > 95%  
Crystallinity up to 85%



Normal PE  
Orientation low  
Crystallinity < 60%



Normal polyethylene has a low orientation and crystallinity generally below 60%;  
Dyneema Purity has an orientation of approx. 98% and crystallinity up to 85%.

	Density	Tensile strength	Tensile modulus	Moisture regain	Thermal expansion	Dielectric cst		Dielectric	Chemical
	g/cm <sup>3</sup>	MPa	GPa	%	10 <sup>-6</sup> .K <sup>-1</sup>	100KHz	1MHz	strength KV/mm	resistance
Zylon-HM	1.56	5800	280	0.6	-6	3	2.1	970	Very good
Vectran	1.4	2800-3200	65-71	< 0,1	-4.8	3,3 à 1 KHz		-	Very good

## Basalt (basaltex)

# Les fibres

Fibres	Avantages	Inconvénients
Verre	<ul style="list-style-type: none"> <li>+++ prix</li> <li>+ rapport performances mécaniques/prix</li> <li>++ résistance spécifique</li> <li>++ caractéristiques diélectriques</li> <li>++ résistance élevée à T</li> <li>++ conductivité et dilatation thermiques faibles</li> </ul>	<ul style="list-style-type: none"> <li>--- vieillissement au contact de l'eau</li> <li>--- résistance aux acides et bases</li> <li>-- densité</li> <li>-- module</li> </ul>
Carbone	<ul style="list-style-type: none"> <li>++++ caractéristiques mécaniques</li> <li>+++ inertie chimique</li> <li>+ densité</li> <li>++ tenue en température</li> <li>++ faible coefficient d'expansion thermique</li> <li>++ bonne conductibilité thermique</li> </ul>	<ul style="list-style-type: none"> <li>--- résistance aux chocs</li> <li>-- résistance à l'abrasion</li> <li>-- Corrosion galvanique au contact des métaux</li> <li>- prix élevé</li> </ul>
Aramide (Kevlar®)	<ul style="list-style-type: none"> <li>++++ résistance aux chocs</li> <li>++ résistance à la traction</li> <li>++ faible densité</li> <li>++ dilatation thermique nulle</li> <li>++ résistance à la fatigue et à l'abrasion</li> <li>++ comportement chimique</li> </ul>	<ul style="list-style-type: none"> <li>--- prix élevé</li> <li>--- usinabilité</li> <li>-- tenue en compression</li> <li>-- prise d'humidité importante</li> <li>-- adhérence à la matrice</li> <li>- décomposition à 400°C</li> </ul>
Polyéthylène (Dyneema®)	<ul style="list-style-type: none"> <li>++++ résistance aux chocs</li> <li>+++ faible densité</li> <li>+++ comportement chimique</li> <li>++ résistance à la traction</li> </ul>	<ul style="list-style-type: none"> <li>----- point de fusion à 150°</li> <li>---- adhérence avec la matrice</li> <li>- usinabilité</li> </ul>

# Les fibres naturelles

Chanvre, lin, jute, sisal, etc...  
Abaca des Philippines, Noix de coco...

<https://www.bcomp.ch/>



<http://www.bmedesign.eu/bamboo-composite-frame>



Thanks to the powerRibs™ technology, it is the first time that natural fibre composites can replace carbon fibres. ©McLaren



Mercedes A200



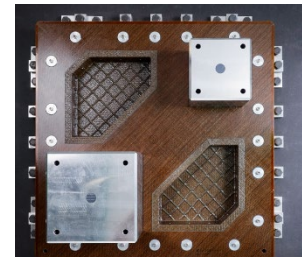
<http://www.notox.fr/>



Stöckli



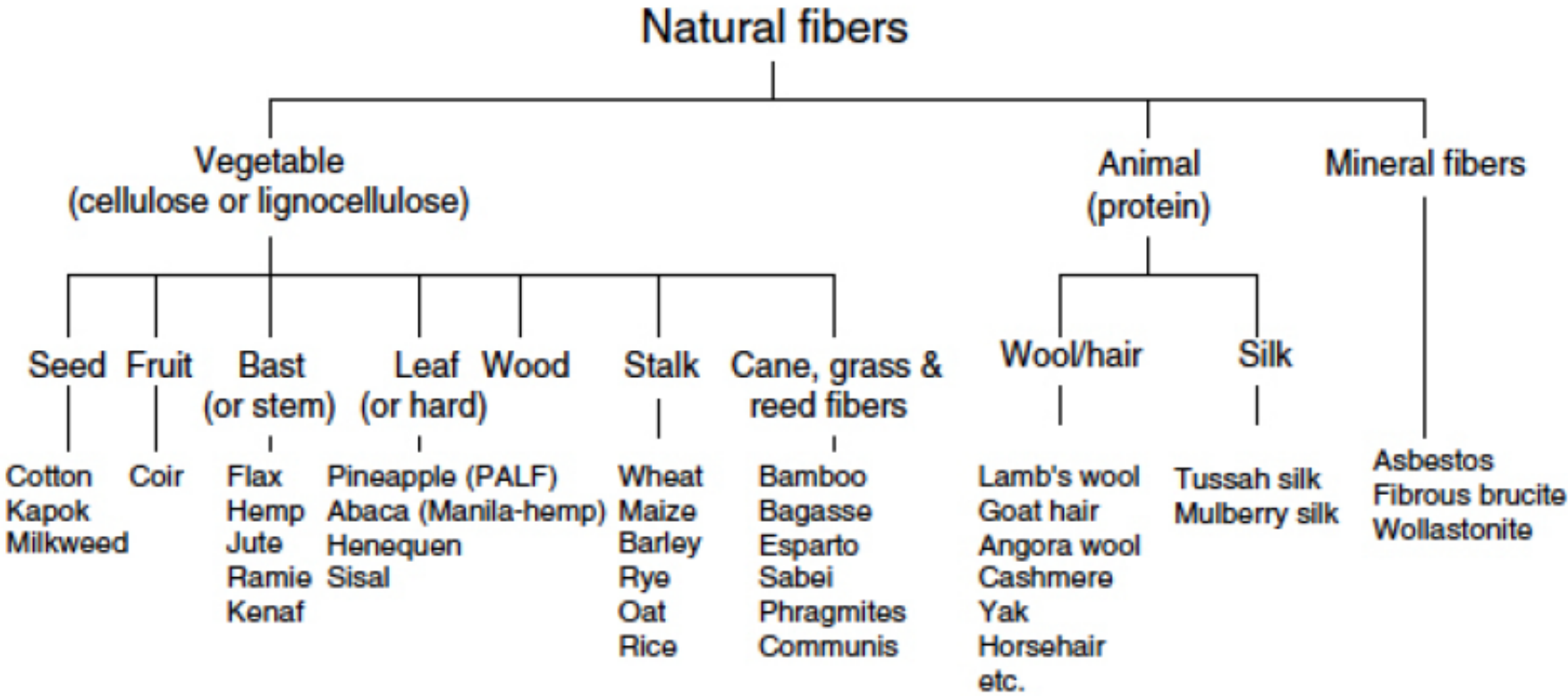
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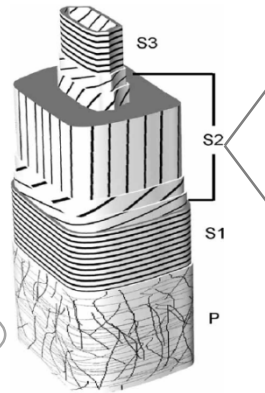
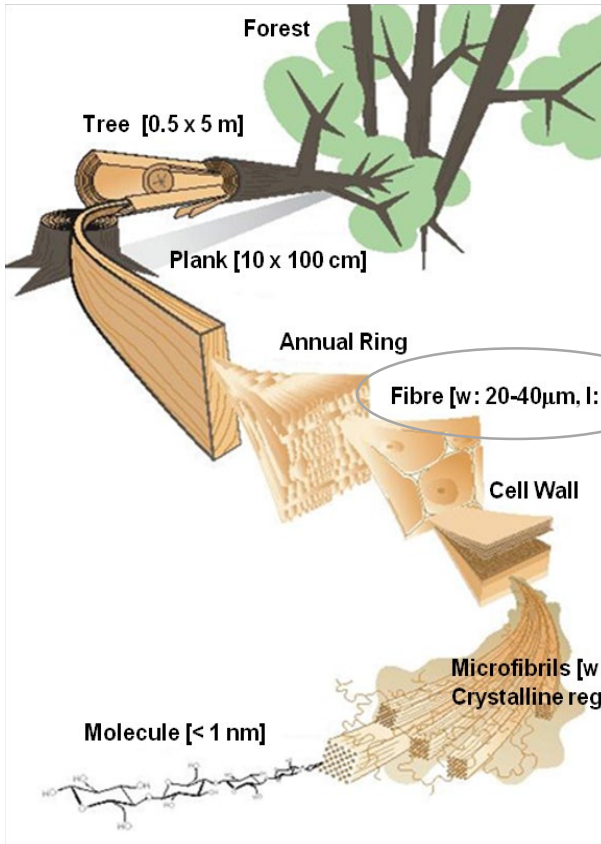
Ritsumasyil record-breaking bio-composite bridge



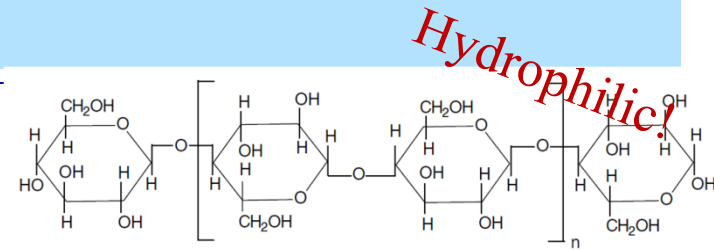
# Fabrication



# Fabrication

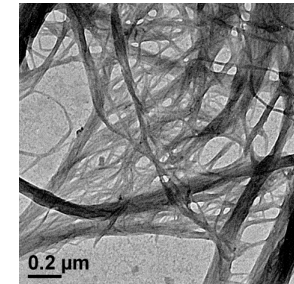
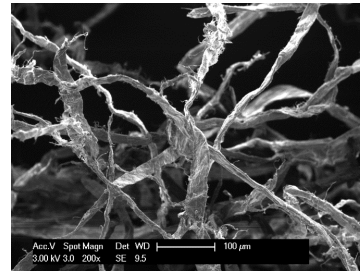


Microfibrils : **Cellulose**  
Matrix : **Hemicellulose and Lignin**



Wood Fiber  
(WF)

Microfibrillated cellulose  
(MFC)



Length $l$	2 to 4 mm	Few $\mu\text{m}$
Diameter $d$	20 to 60 $\mu\text{m}$	10-100 nm
Aspect ratio $(l/d)$	$\sim 80$	$\sim 100$
Young's Modulus (GPa)	40	70-130 (?)

\* adapted from Neagu et al., PhD Thesis, KTH, 2006 and Mathew et al., 2005

# Propriétés

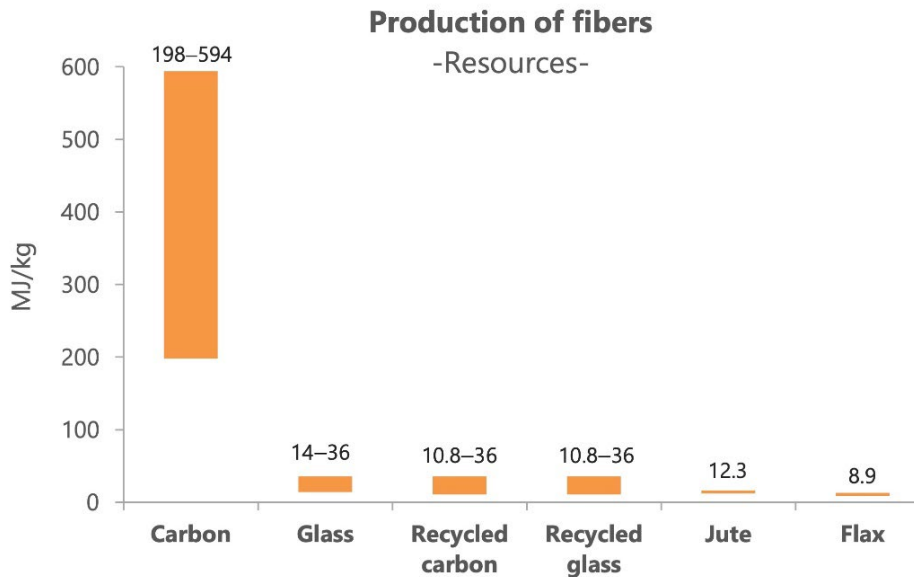
Fiber	Density (g cm <sup>-3</sup> )	Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Flax	1.5	40–600	345–1500	27.6	2.7–3.2
Hemp	1.47	25–500	690	70	1.6
Jute	1.3–1.49	25–200	393–800	13–26.5	1.16–1.5
Kenaf			930	53	1.6
Ramie	1.55	—	400–938	61.4–128	1.2–3.8
Nettle			650	38	1.7
Sisal	1.45	50–200	468–700	9.4–22	3–7
Henequen					
PALF		20–80	413–1627	34.5–82.5	1.6
Abaca			430–760		
Oil palm EFB	0.7–1.55	150–500	248	3.2	25
Oil palm mesocarp			80	0.5	17
Cotton	1.5–1.6	12–38	287–800	5.5–12.6	7–8
Coir	1.15–1.46	100–460	131–220	4–6	15–40
E-glass	2.55	<17	3400	73	2.5–4.5
Kevlar	1.44		3000	60	2.5–3.7
Carbon	1.78	5–7	3400 <sup>a</sup> –4800 <sup>b</sup>	240 <sup>b</sup> –425 <sup>a</sup>	1.4–1.8

<sup>a</sup> Ultra high modulus carbon fibers.

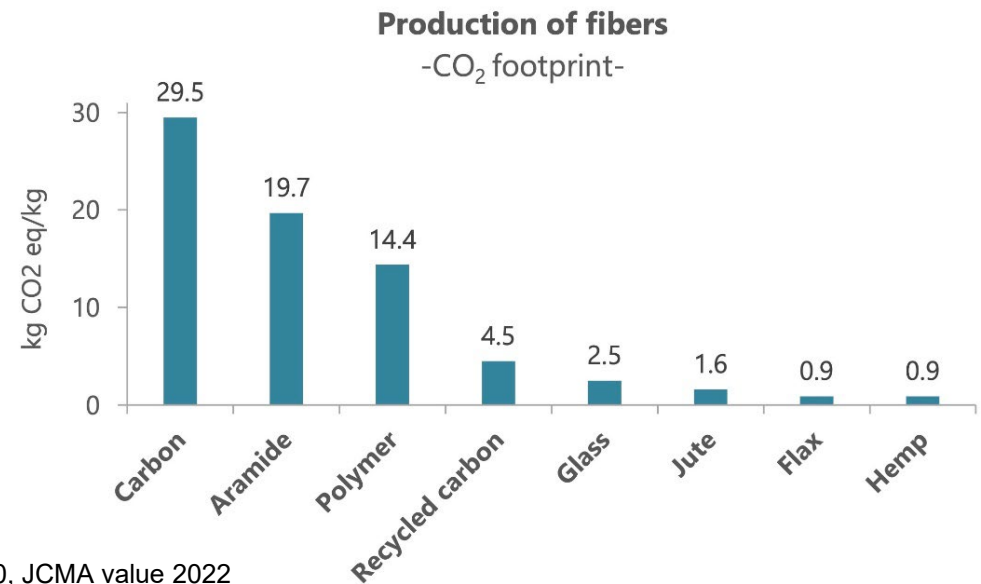
<sup>b</sup> Ultra high tenacity carbon fibers.

+ écologiques, peu chères, bonne tenue mécanique  
- dispersion des propriétés, mise en oeuvre

# Ressources nécessaires et impact CO<sub>2</sub> d'un kilo de fibres



350, JCMA value 2022



20, JCMA value 2022

Sources: Ecoinvent database; JEC observer 2021: Current trends in the global composite industry 2020-2050; Niels de Beus, Michael Carus, Martha Barth. 2019: Carbon footprint and sustainability of different natural fibres for biocomposite and insulation material, Teijin website, Dyneema website, JCMA website

# Critères de choix des fibres

Cahier des charges du produit à réaliser:

- compromis rigidité/masse/coût
- élongation à rupture
- température d'utilisation
- résistance à l'impact, en compression, en cisaillement...
- résistance chimique, aux UV, corrosion
- conductivité électrique, thermique
- coefficient d'expansion thermique de la pièce
- compatibilité avec la matrice choisie
- choix de la technique de mise en oeuvre

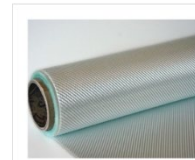
# Prix des fibres

Swiss-Composite.ch/ Global tools, : on line stores  
in CHF/kg, bobbins

Glass : 5-15  
Kevlar: ~100  
Carbon (HTS): 1k : 800  
3k : 274  
6k : 147  
12k : 100  
24k : 122  
60k : 80  
Basalt: 10-15

In CHF/m<sup>2</sup>, fabrics

3-10 for 100 à 200g/m<sup>2</sup>  
~ 30  
30 to 100



des fibres de verre



des fibres de carbone



aramides



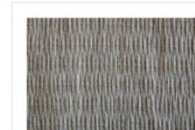
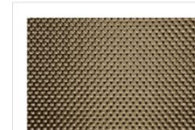
fibre mixte / hybride



Préimprégné de carbone

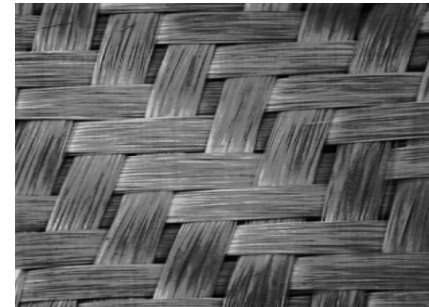
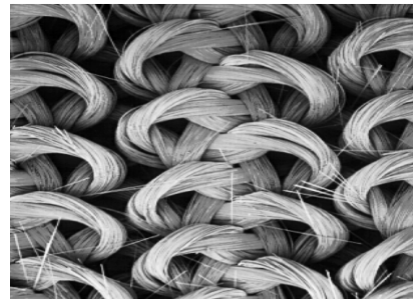
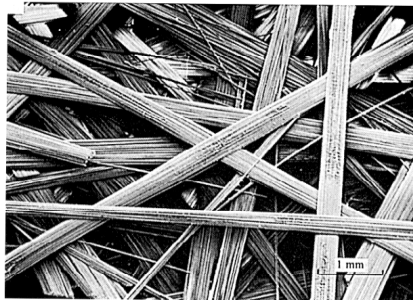


Peel ply

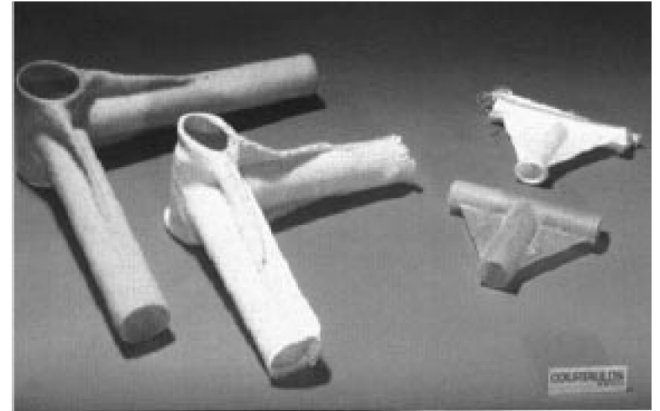
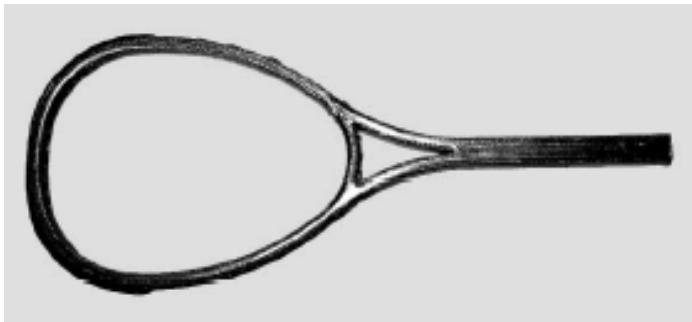
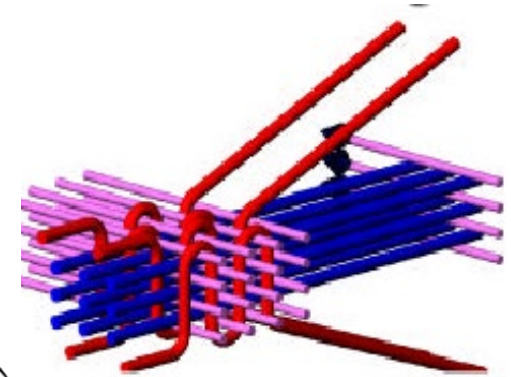
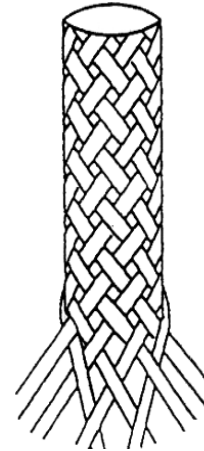
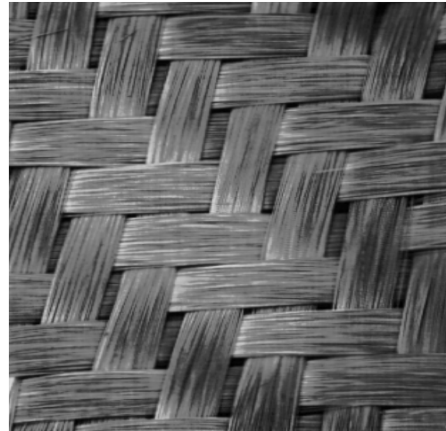


# Potentiels de renforcement

<b>Matériaux</b>	Verre	Aramide	Acier	Carbone	
	<i>E Module (Gpa)</i>			400	
<b>Forme</b>	Particules	Fibres: courtes	longues	discontinues	continues
	1	<i>Facteur de forme L/d</i>			$\infty$
<b>Configuration</b>	Aléatoire	Tricot	Tissu		
	0	<i>Orientation</i>		1	



# Les composites textiles



# Les matrices polymères

## Thermodurcis

Avantages

- + Résines liquides à l'ambiante
- + Facilité de mise en oeuvre (EP, UP)
- + Durcissement entre 5 et 180C (EP)
- + Prix raisonnable
- + Grande variété de formulation possibles
- + Bonne adhésion aux fibres
- + Résistance à la température variable

Inconvénients

- Volatilité, toxicité, allergies
- Résistance à l'humidité
- Résistance aux chocs
- Contrôle de la réaction chimique

## Thermoplastiques

Avantages

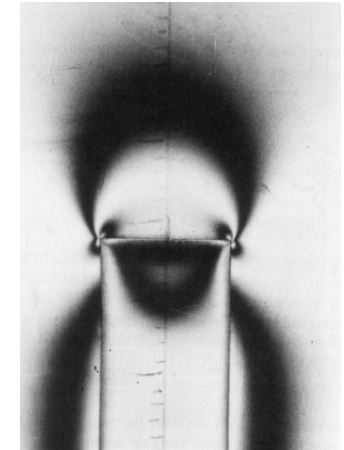
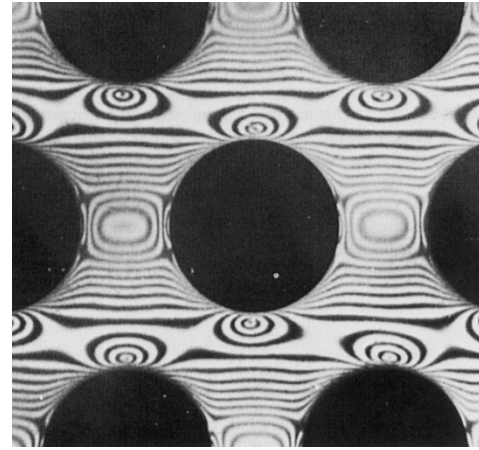
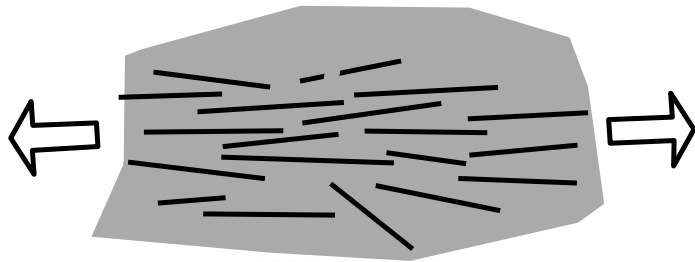
- + Mise en oeuvre rapide, par élévation de T
- + Procédés de mise en oeuvre des thermoplastiques utilisable avec les fibres courtes
- + Bonne résistance à l'humidité

Inconvénients

- Souvent peu résistantes à la T
- Retrait au moulage (matrices s- c)
- Mauvaise résistance chimique
- Adhésion aux fibres souvent problématique
- Propriétés mécaniques faibles, fluage

# Les matrices polymères

Rôle de la matrice: assurer le transfert et la répartition des charges (contraintes) entre les fibres



Visualisation des isochromes (lignes d'isocontraintes) dans une matrice polymère enrobant des fibres et à la pointe d'une fibre

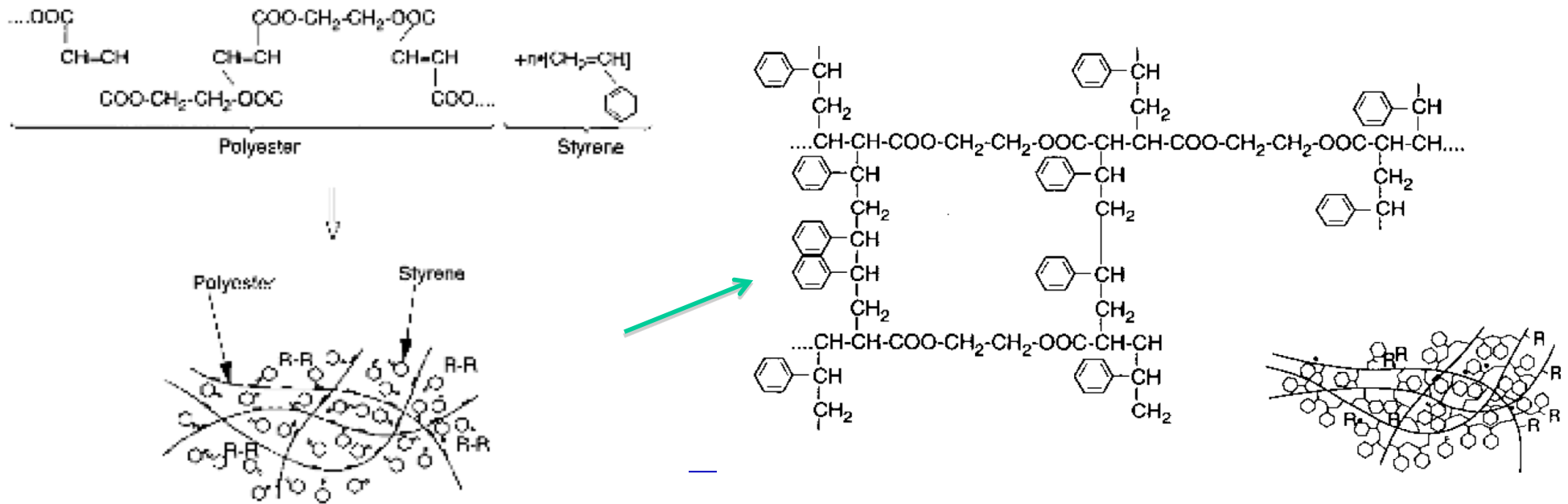
## • Matrice idéale:

- Faible viscosité (pour imprégner facilement les fibres)
- Propriétés mécaniques élevées
- Bonne résistance thermique
- Bonne résistance chimique et à l'humidité
- Adhésion élevée aux fibres
- Faible retrait à la mise en œuvre
- Résistance au feu et à l'émission des gaz toxiques
- Bas prix

# Les matrices thermodurcissables

Polyesters insaturés : couramment utilisés (coques, grands panneaux, automobile).

Préparation: en solution dans le styrène, ajout de catalyseur et d'inhibiteurs de réaction.

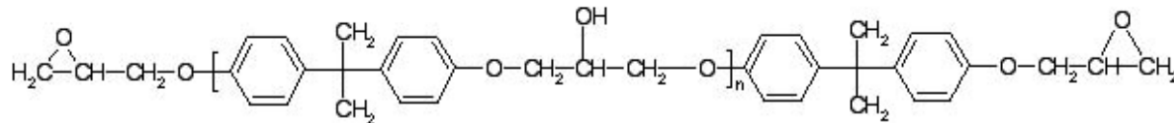


# Les matrices thermodurcissables

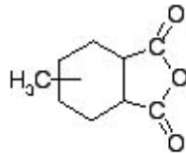
Epoxydes: Découvertes en Suisse par Ciba en 1943.

Préparation: monomère et durcisseur (amine ou anhydride)  
-> réseau tridimensionnel, insoluble et infusible

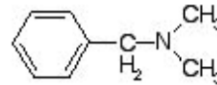
Diglycidyl ether of bisphenol A - DGEBA



Methyl-hexahydrophthalic anhydride - MHHPA



Benzyl-dimethylamine - BDMA



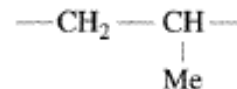
# Les matrices thermoplastiques

## Thermoplastiques linéaires, amorphes ou semi-cristallins

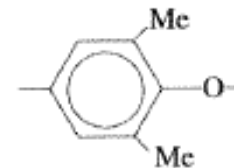
Polyamide (PA)



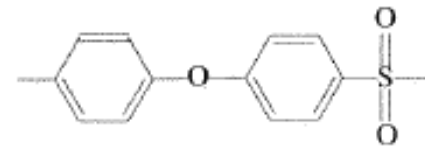
Polypropylène (PP)



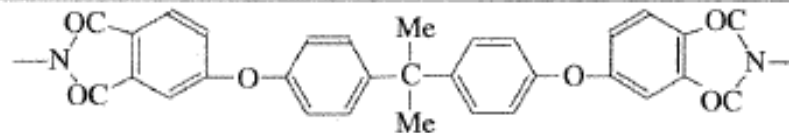
Poly(2,6-diméthyl-1,4-phénylène éther)  
(PPE) amorphe



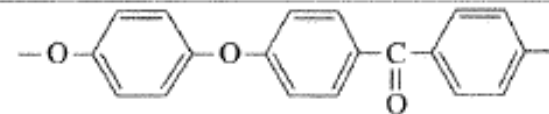
Poly(*p*-phénylène-éther-sulfone)  
(PES) amorphe



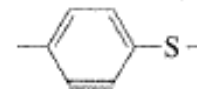
Polyétherimide  
(PEI)  
amorphe



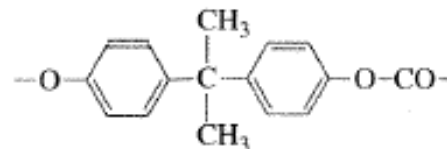
Poly(*p*-phénylène-éther-éther-cétone)  
(PEEK) semicristallin



Poly(sulfure de *p*-phénylène)  
(PPS) semicristallin



Polycarbonate de bisphénol-A  
(PC) amorphe



# Prix et températures de transition

Type	Abbreviation	Prices		Transition temperatures	
		(\$lb <sup>-1</sup> )	(\$kg <sup>-1</sup> )	T <sub>g</sub> (°C)	T <sub>m</sub> (°C)
<b>Polyolefins</b>					
Polyethylene, low-density	LDPE	0.41	0.90	- 90	120
Polyethylene, high-density	HDPE	0.39	0.86	- 30	135
Polypropylene	PP	0.28	0.62	- 20	165
<b>Styrenics</b>					
Polystyrene, "crystal"	PS	0.39	0.86	100	am
Polystyrene, impact mod.	HIPS	0.44	0.97	100	am
Acrylonitrile/butadiene/styrene	ABS	0.90	1.98	100	am
Styrene/acrylonitrile	SAN	0.87	1.91	110	am
Styrene/acrylic	S/A	1.10	2.42	100	am
Styrene/maleic anhydride	SMA	1.13	2.48	115	am
<b>Vinyls</b>					
Polyvinyl chloride	PVC	0.37	0.82	85	am
Chlorinated PVC	CPVC	1.19	2.62	100	am
<b>Acrylics</b>					
Polymethylmethacrylate	PMMA	0.85	1.87	100	am
PVC/acrylic blend	PVC/MA	1.50	3.31	90	am
<b>Fluoropolymers</b>					
Polychlorotrifluoroethylene	CTFE	45.00	99.18	30	235
Polytetrafluoroethylene	PTFE	7.00	15.43	27	325
Polyvinylidene fluoride	PVDF	6.75	14.88	- 30	170
<b>Polyesters</b>					
Polyethylene terephthalate	PET	0.54	1.19	80	250
Polyester, PETG	PETG	0.98	2.16	80	am
Polybutylene terphthalate	PBT	1.45	3.20		235
Polyarylate	PAR	2.40	5.29	190	am
Liquid crystal polyester	LCP	12.00	26.45		400

# Prix et températures de transition

Polyamides (nylons)					
Nylon type 6	N6	1.30	2.87	60	220
Nylon type 66	N66	1.40	3.07	70	260
Nylon type 11	N11	3.35	7.38	- 70	185
Nylon type 12	N12	3.30	7.26		190
Polyphthalamide	PPA				310
Polyamideimide	PAI	26.10	57.52	275	am
Polyimides					
Polyetherimide	PEI	6.41	14.13	215	am
Polyimide	PI			320	385
Polyethers					
Polyacetal	POM	1.25	2.76	- 75	175
Polycarbonate	PC	1.55	3.42	150	am
Polyphenylene oxide blend	PPO	1.80	3.97	110-190	am
Polyaryletherketone	PAEK	29.50	65.02	138	320-380
Polyetheretherketone	PEEK	33.00	72.73	145	335
Sulfur-containing polymers					
Polyphenylene sulfide	PPS			90	285
Polysulfone	PSF	4.40	9.70	190	am
Polyethersulfone	PES	4.40	9.70	225	am
Polyarylsulfone	PAS	4.40	9.70	220	am
Additional thermoplastics					
Acrylonitrile copolymer	ANC	1.25	2.76	95	am
Polyurethane	TPU	2.10	4.63		am

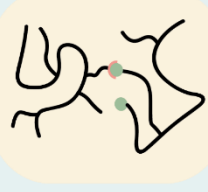
# Vitrimères

## Thermoplastics



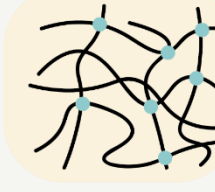
- No crosslinks
- Reprocessable
- Recyclable
- Viscosity drop when heated
- Low thermal/chemical resistance

## Vitrimers



- Dynamic crosslinked network
- Poor thermal/chemical resistance
- Malleable when heated
- Reprocessable
- Recyclable

## Thermosets



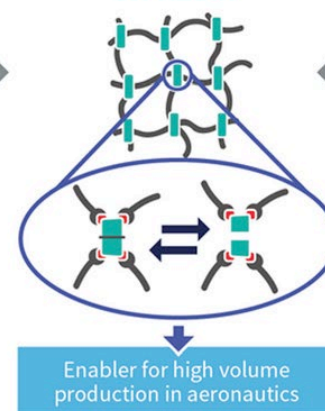
- Crosslinked network
- Good mechanical properties
- High thermal/chemical resistance
- Non-reprocessible
- Non-recyclable
- Often low viscosity



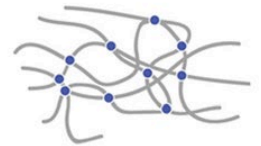
### THERMOPLASTIC

- Entangled linear polymer chains
- Reprocessable
- Recyclable
- Soluble
- Bad chemical resistance
- Softens when heated

### AIRPOXY 3R RESIN



Enabler for high volume production in aeronautics

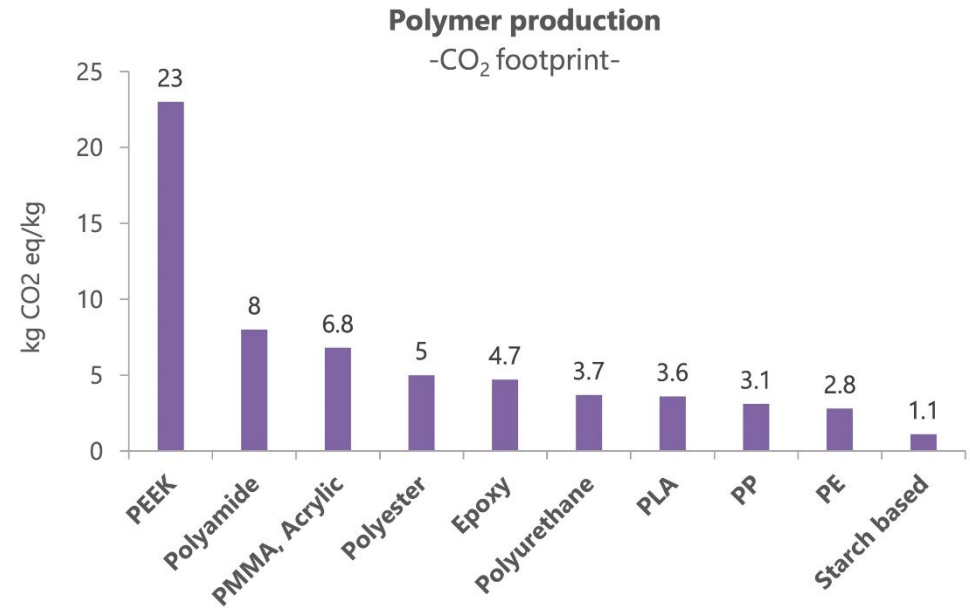
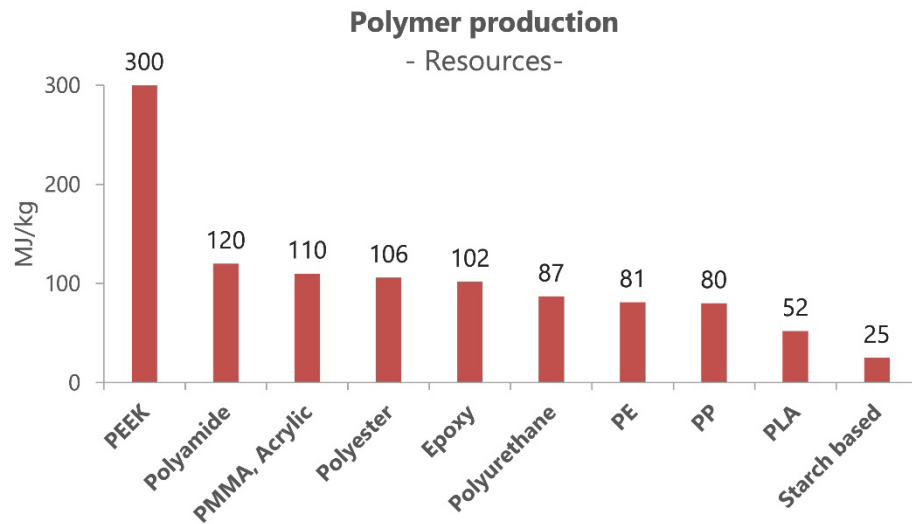


### THERMOSET

- Covalently crosslinked
- Remains hard when heated
- Insoluble
- Chemical resistance
- Good mechanical properties
- Non-processable
- Non-recyclable

Short cycle times · New repair concepts · Welding · Transport at room temperature · Recycling

# Ressources nécessaires et impact $CO_2$ d'un kilo de matrice



Sources: Ecoinvent database; Ashby, Materials and sustainable development

# Les matrices: exemples d'applications

## Thermodurcis

Matrice	Applications	propriétés
Epoxydes (EP)	Avionique, sport et loisirs (skis, tennis, voile, casques, F1), circuits imprimés, robots	Excellente adhésion, bonnes propriétés mécaniques et chimiques
Polyesters (UP)	Génie civil, architecture, voile (loisir)	Bon marché, faible viscosité, bonne résistance chimique
Phénoliques (PF)	Connectique, mécanique, composites HT, imprégnation de noyau pour sandwich	Fragile, résistant à la T
Polyimides (PI)	Connectique, mécanique, composites HT (200°C)	Fragile, difficile à mettre en œuvre, résistant à la T

## Thermoplastes

Polyétheréthercétone (PEEK)	Avionique, pièces technique (palliers), composites HT	S-C, Tf : 334°C, T <sub>max</sub> : 240°C Disponible sous forme de préimprégnés
Polysulfone (PSU)	Connecteurs, pièces mécaniques, microtechnique	Amorphe, T <sub>g</sub> : 320°C, T <sub>max</sub> : 220°C
Polysulfure de phénylène (PPS)	Mécanique, microtechnique	S-C, Tf : 288°C, T <sub>max</sub> : 240°C
Polyamide (PA)	Dans tous les domaines	S-C, Tf : 176-220°C, T <sub>max</sub> : 110°C
Polyester (PET, PBT)	Mécanique, microtechnique	S-C, T <sub>g</sub> : 70°C, T <sub>max</sub> : 110°C
Polycarbonate (PC)	Mécanique, microtechnique	Amorphe, T <sub>g</sub> : 141°C, T <sub>max</sub> : 120°C
Polypropylène (PP)	Automobile (pare-chocs, pièces de carrosserie), microtechnique	S-C, Tf : 140°C, T <sub>max</sub> : 90°C

# Les classes de composites

## Composites de grande diffusion

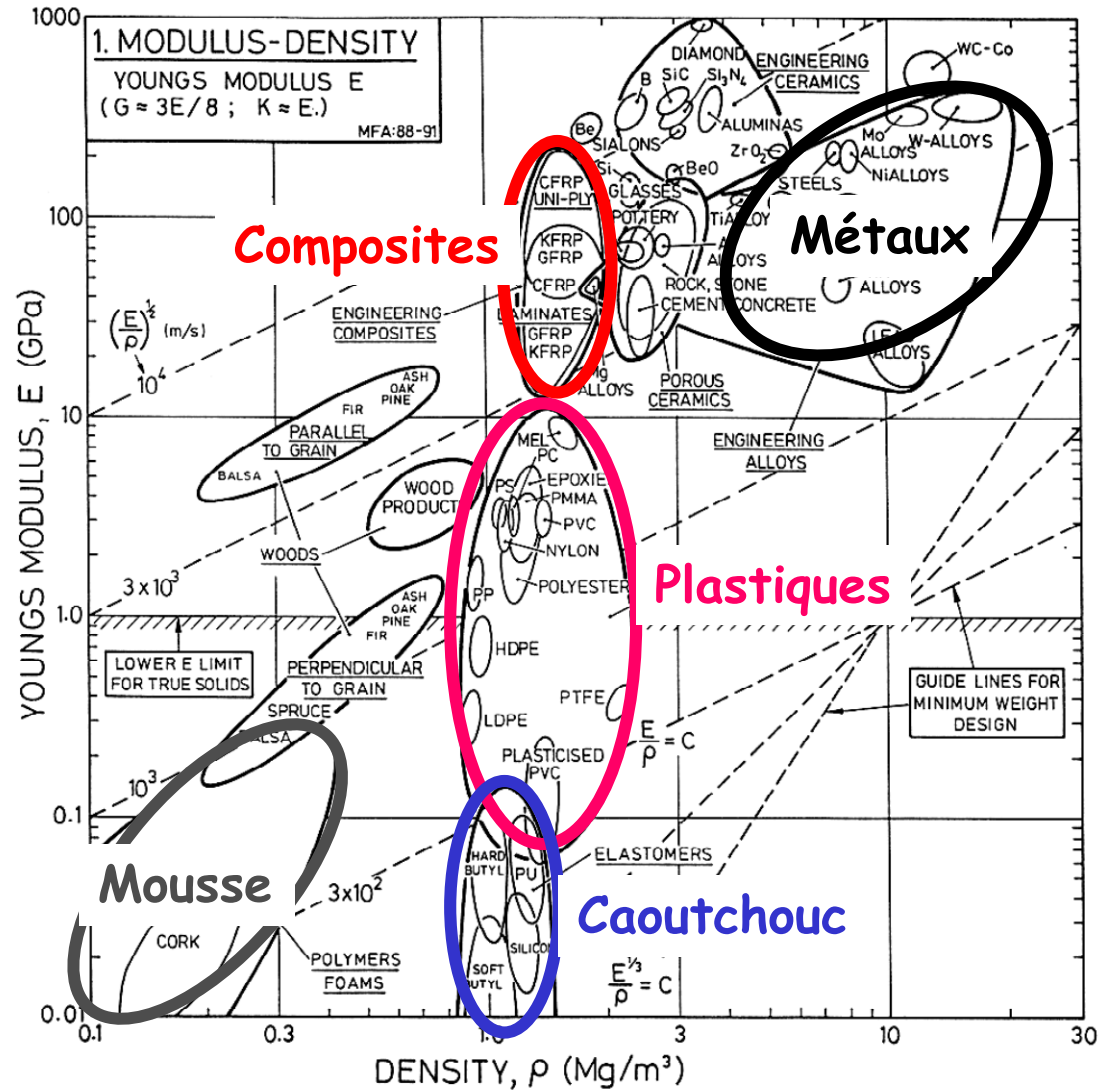
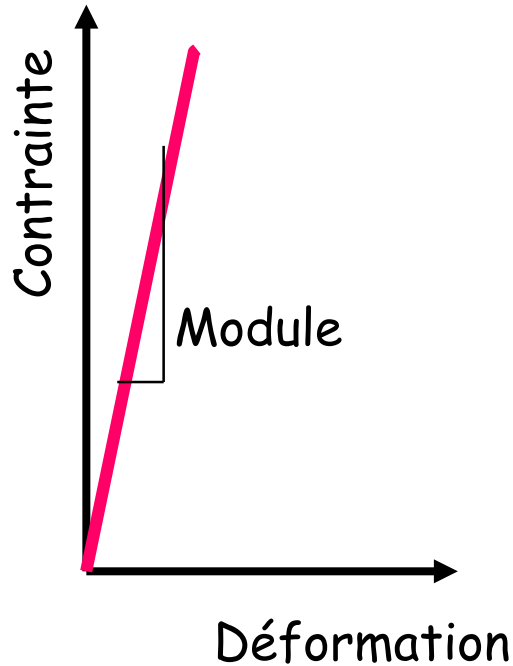
Matrices	Renforts	Applications
Polyester Vinylester Epoxyde Polypropylene Polyamide ...	fibres de verre (mats, tissus, fibres courtes)	- bateaux - carrosserie d'automobiles et de trains - canalisations, réservoir - génie chimique ....

## Composites hautes performances

Matrices	Renforts	Applications
Polyetherethercétone (PEEK) Polyimides Polyphenylene sulfide (PPS) Epoxyde ...	carbone, aramide, (unidirectionnels , tissus)	- éléments d'avions - raquettes de tennis, club de golf... - pales d'hélicoptère ....

# Propriétés des composites: module - densité

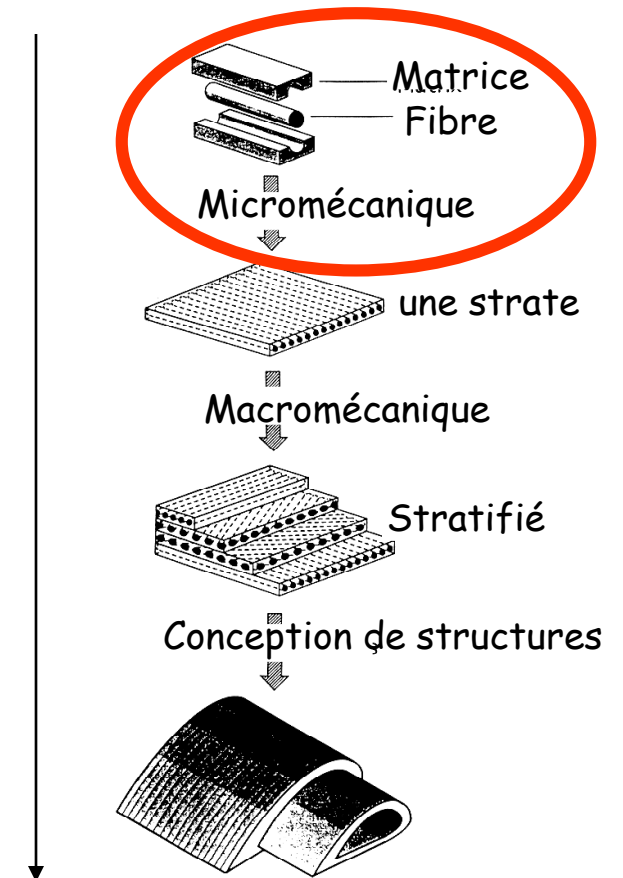
Propriétés spécifiques élevées



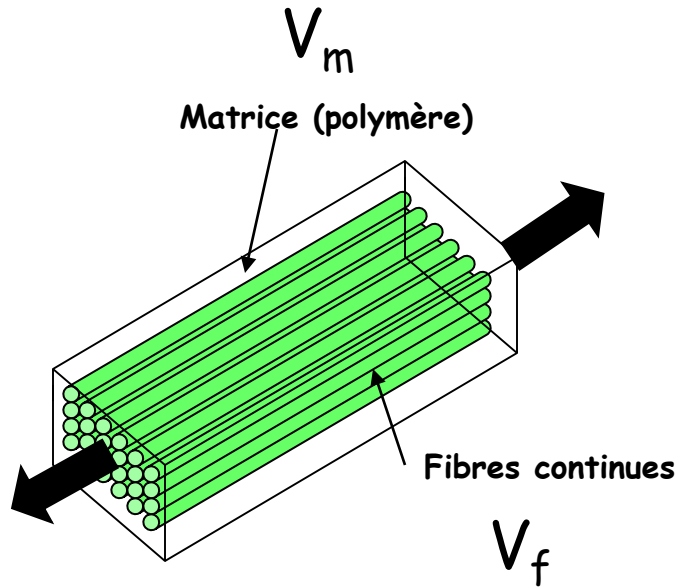
M.F. Ashby, Materials Selection for Mechanical design, Pergamon Press

# Micromécanique

- Introduction
- Lois des mélanges
- Fibres courtes



# Fibres continues: propriétés longitudinales



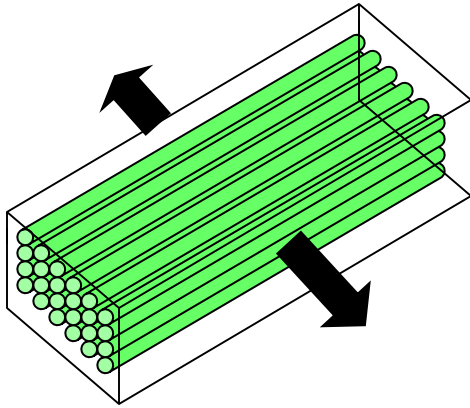
$$\varepsilon_f = \varepsilon_m = \varepsilon_L$$

$$F = F_m + F_f$$

$$E_1 = E_f V_f + E_m (1 - V_f) = E_L$$

# Fibres continues: propriétés transversales

$$d = d_m + d_f$$



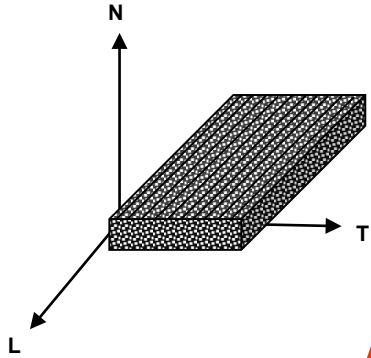
$$E_2 = \frac{E_m E_f}{E_f (1 - V_f) + E_m V_f} = E_T$$

# Propriétés des matériaux composites unidirectionnels

	MÉTAUX			COMPOSITES A MATRICE ORGANIQUE			
	Ac35NDC1	Alliage Al	Alliage Ti	Bore époxy	Carbone HF époxy	Carbone HM époxy	Verre R époxy
<b>Module de Young E</b> (MPa)	200'000	72'000	110'000	220'000	130'000	200'000	53'000
<b>Résistance à la rupture en traction</b> $\sigma_r$ (MPa)	1850	500	1000	2000	1000 à 1300	1000	1800 à 2000
<b>Masse volumique <math>\rho</math></b> (g/cm <sup>3</sup> )	7.9	2.8	4.45	2.1	1.5	1.7	2
<b>Module spécifique</b> $E/\rho$ (MPam <sup>3</sup> /kg)	25	25	25	105	87	118	26
<b>Résistance spécifique</b> $\sigma/\rho$ (MPam <sup>3</sup> /kg)	0.24	0.18	0.23	0.95	0.65 à 0.85	0.60	0.90 à 1

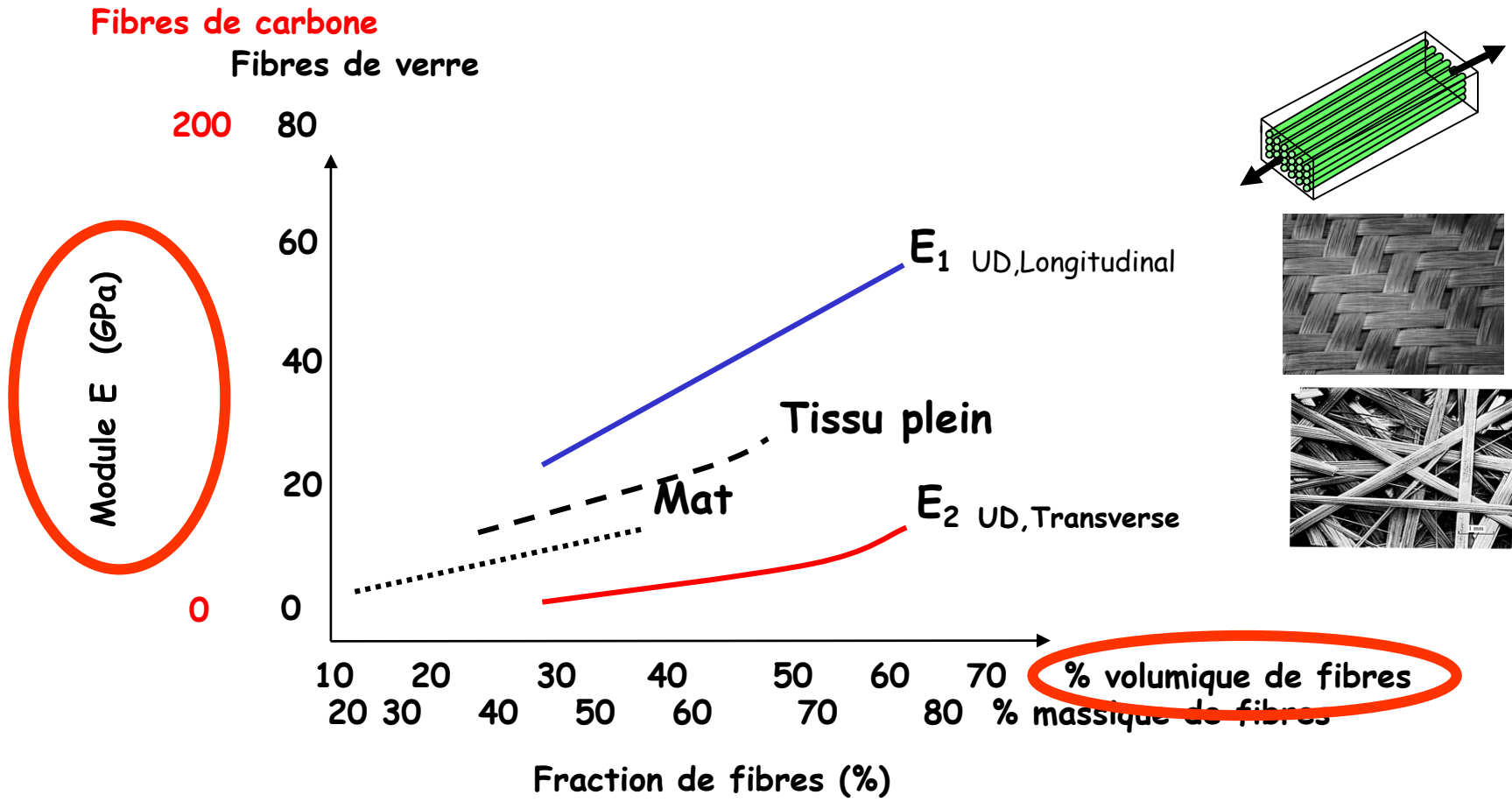
Propriétés de composites unidirectionnels avec 60% de fibres en volume

# Propriétés des composites unidirectionnels



	Verre S Epoxy	Kevlar 49 Epoxy	Carbone HR Epoxy	Carbone HM Epoxy	Bore Epoxy
<b>vf</b>	65 %	65 %	65 %	65 %	55 %
<b>Densité <math>\rho</math></b>	2.04 g/cm <sup>3</sup>	1.36 g/cm <sup>3</sup>	1.56 g/cm <sup>3</sup>	1.5 g/cm <sup>3</sup>	1.97 g/cm <sup>3</sup>
<b>E<sub>L</sub></b>	56 GPa	86 GPa	145 GPa	270 GPa	220 GPa
<b>E<sub>T</sub></b>	16 GPa	5.6 GPa	10 GPa	7 GPa	2.3 GPa
<b><math>\nu_{LT}</math></b>	0.26	0.32	0.29	0.3	0.26
<b>G<sub>LT</sub></b>	7 GPa	2.5 GPa	5.5 GPa	5.7 GPa	6.9 GPa
<b><math>\sigma_{rL}</math> traction</b>	1.75 GPa	1.5 GPa	1.2 GPa	0.95 GPa	1.3 GPa
<b><math>\sigma_{rT}</math> traction</b>	0.04 GPa	0.03 GPa	0.08 GPa	0.035 GPa	0.065 GPa
<b><math>\sigma_{rL}</math> compression</b>	0.9 GPa	0.28 GPa	1 GPa	0.75 GPa	2.85 GPa
<b><math>\sigma_{rT}</math> compression</b>	0.15 GPa	0.14 GPa	0.25 GPa	0.2 GPa	0.03 GPa
<b><math>\gamma_{rLT}</math> cisaillement</b>	0.06 GPa	0.05 GPa	0.1 GPa	0.055 GPa	0.06 GPa

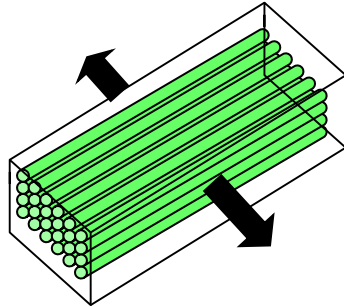
# Rigidités à volonté



# Equations de Halpin-Tsai

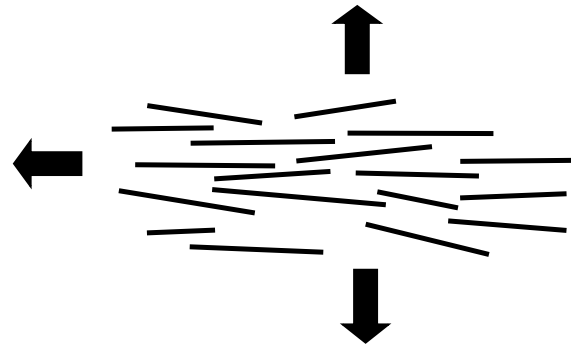
$$P = \frac{P_m (1 + \xi \chi V_f)}{1 - \chi V_f}$$

$$\chi = \frac{P_f - P_m}{P_f + \xi P_m}$$



$$\xi(E_T) = 2$$

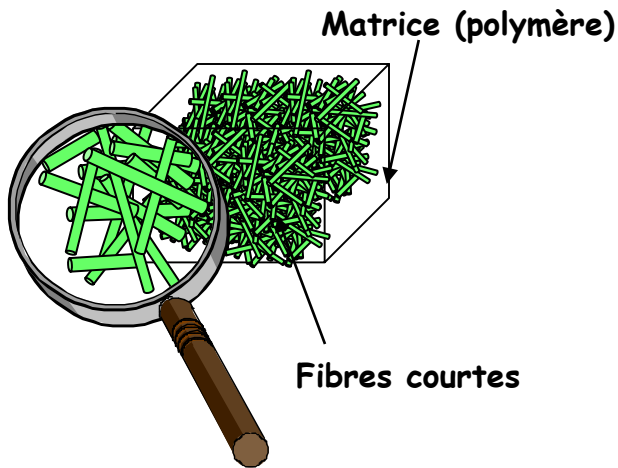
$$\xi(G_{LT}) = 1$$



$$\xi = 2 + 40 V_f^{10}$$

$$\xi = \frac{21}{d} + 40 V_f^{10}$$

# Composites à fibres discontinues



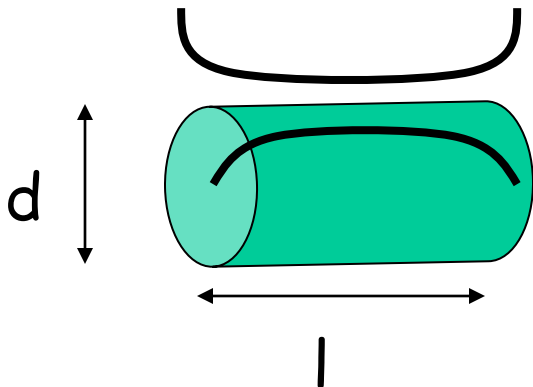
Facteur de formes  $l/d$

Fraction volumique  $V_f$

Qualité des interfaces

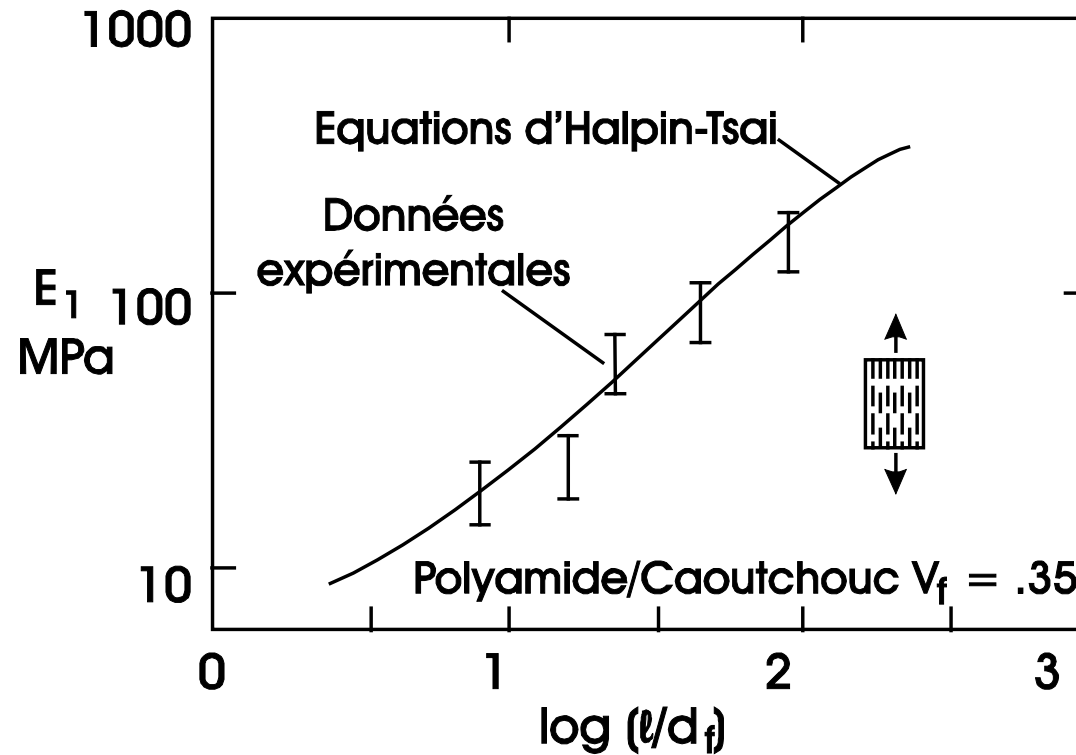
Distribution statistique de l'orientation des fibres

Distribution de la longueur des fibres



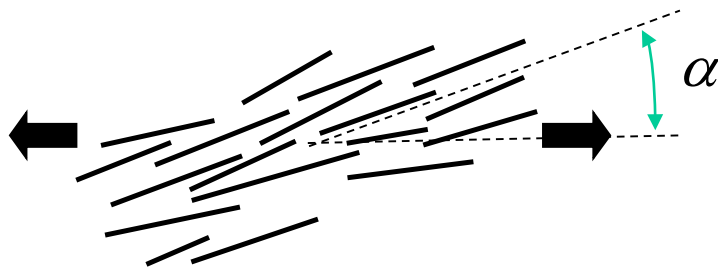
$$E = \eta_{\text{orientation}} \eta_{\text{longueur fibre}} E_f V_f + E_m (1 - V_f)$$

# Composites à fibres courtes



# Composites à fibres courtes orientées

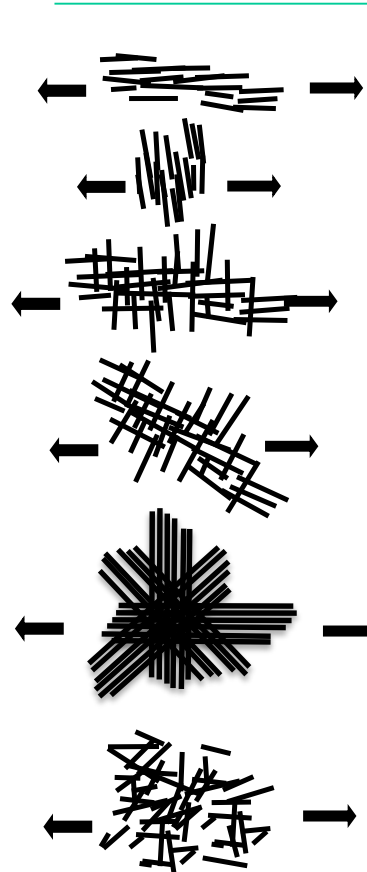
$$E = \eta_{orientation} \eta_{longueur\ fibre} E_f V_f + E_m (1 - V_f)$$



$$\eta_{orientation} \approx \cos^4 \alpha$$

$$\eta_{orientation} \approx \sum_n p_n \cos^4 \alpha_n$$

$$\sum_n p_n = 1$$



$$p_n =$$

$$\eta_o =$$

$$p_n = 1$$

$$\eta_o = 1 \cos^4 0 = 1$$

$$p_n = 1$$

$$\eta_o = 1 \cos^4 90 = 0$$

$$p_1 = p_2 = \frac{1}{2}$$

$$\eta_o = \frac{1}{2} \cos^4 0 + \frac{1}{2} \cos^4 90 = \frac{1}{2}$$

$$p_1 = p_2 = \frac{1}{2}$$

$$\eta_o = \frac{1}{2} \cos^4 45 + \frac{1}{2} \cos^4 (-45) = \frac{1}{4}$$

$$p_1 = p_2 = p_3 = p_4 = \frac{1}{4}$$

$$\eta_o = \frac{1}{4} (\cos^4 0 + \cos^4 90 + \cos^4 45 + \cos^4 (-45)) = \frac{3}{8}$$

Aléatoire 3dim

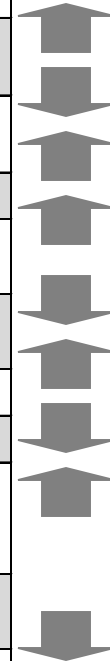
$$\eta_o = \frac{1}{5}$$

Aléatoire 2dim

$$E = \frac{3}{8} E_0 + \frac{5}{8} E_{90}$$

# Propriétés des polymères chargés de fibres courtes

Propriété à 23°C	Zytel®		Zytel® 40% fibres courtes		Zytel® 50% fibres courtes	
	0 % HR	50% HR	0 % HR	50% HR	0 % HR	50% HR
Contrainte au seuil plastique $\sigma_y$ (MPa)	84 MPa	48 MPa	205 MPa	135 MPa	230 MPa	155 MPa
Allongement à la rupture $\varepsilon_y$ (%)	50 %	>300 %	3 %	6 %	2 %	5 %
Module de flexion E	2.7 GPa	0.9 GPa	10.5 GPa	6.5 GPa	23.5 GPa	8.5 GPa
Résistance au choc entaillé Izod	50 J/m	200 J/m	160 J/m	214 J/m	180 J/m	270 J/m
Résistance au choc Charpy	Pas de rupture		60 kJ/m <sup>2</sup>		65 kJ/m <sup>2</sup>	
Densité $\rho$	1.14 g/cm <sup>3</sup>		1.45 g/cm <sup>3</sup>		1.58 g/cm <sup>3</sup>	
Point de fusion	245°C		233 °C		233 °C	
Température de flexion sous charge de 1.8 MPa	65 °C		224 °C			
Absorbion d'eau en 24h (immersion)	1.6 %					
Retrait au moulage	1.3 %		0.18 %		0.16 %	

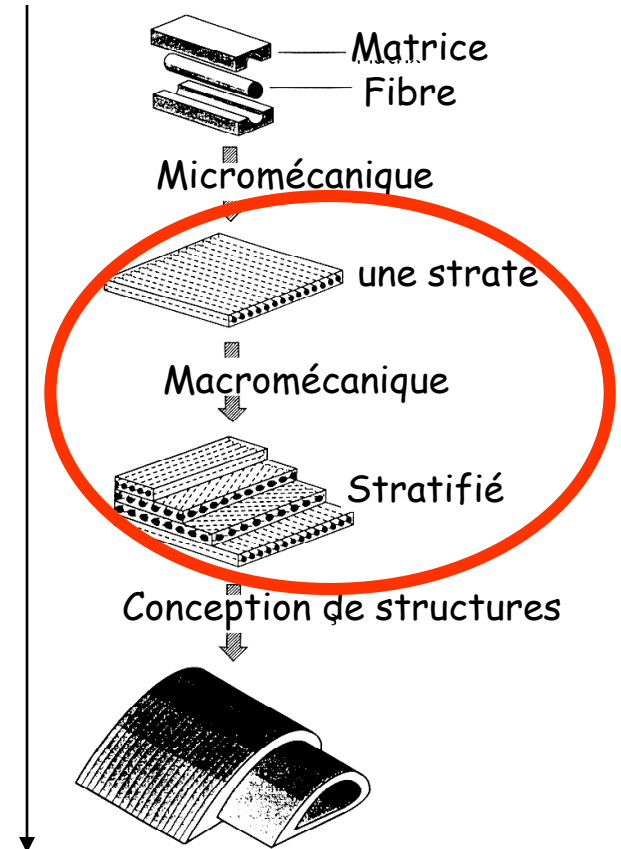


Comparaison des propriétés d'un copolymère PA66/6 (Nylon)  
non chargé et chargé avec des fibres courtes

[matweb.com](http://matweb.com)

# Macromécanique

- Introduction, tenseurs, anisotropie
- Comportement d'une strate
- Composites orthotropes  
sous contraintes planes
- Comportement du stratifié

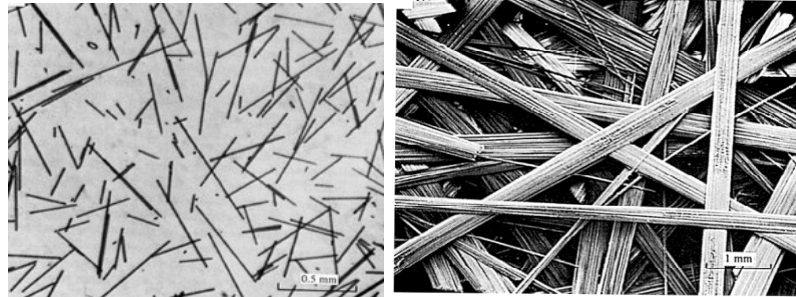
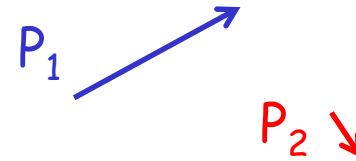


# Anisotropie

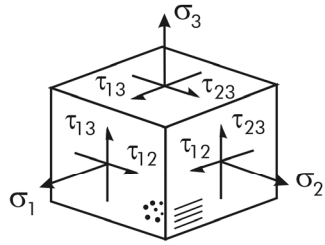
Matériaux homo ou hétérogènes



Matériaux iso ou anisotropes



# Elasticité des matériaux anisotropes



Propriétés élastiques  
du composite

Matériaux anisotropes

81 cstes

Linéaire et élastique

Loi de Hooke

Les contraintes et les  
déformations sont  
symétriques

36 cstes

Densité d'énergie de déformation

21 cstes

$$C_{ij} = C_{ji}$$

Symétries du matériau

Monoclinique

13 cstes

Orthotropie

9 cstes

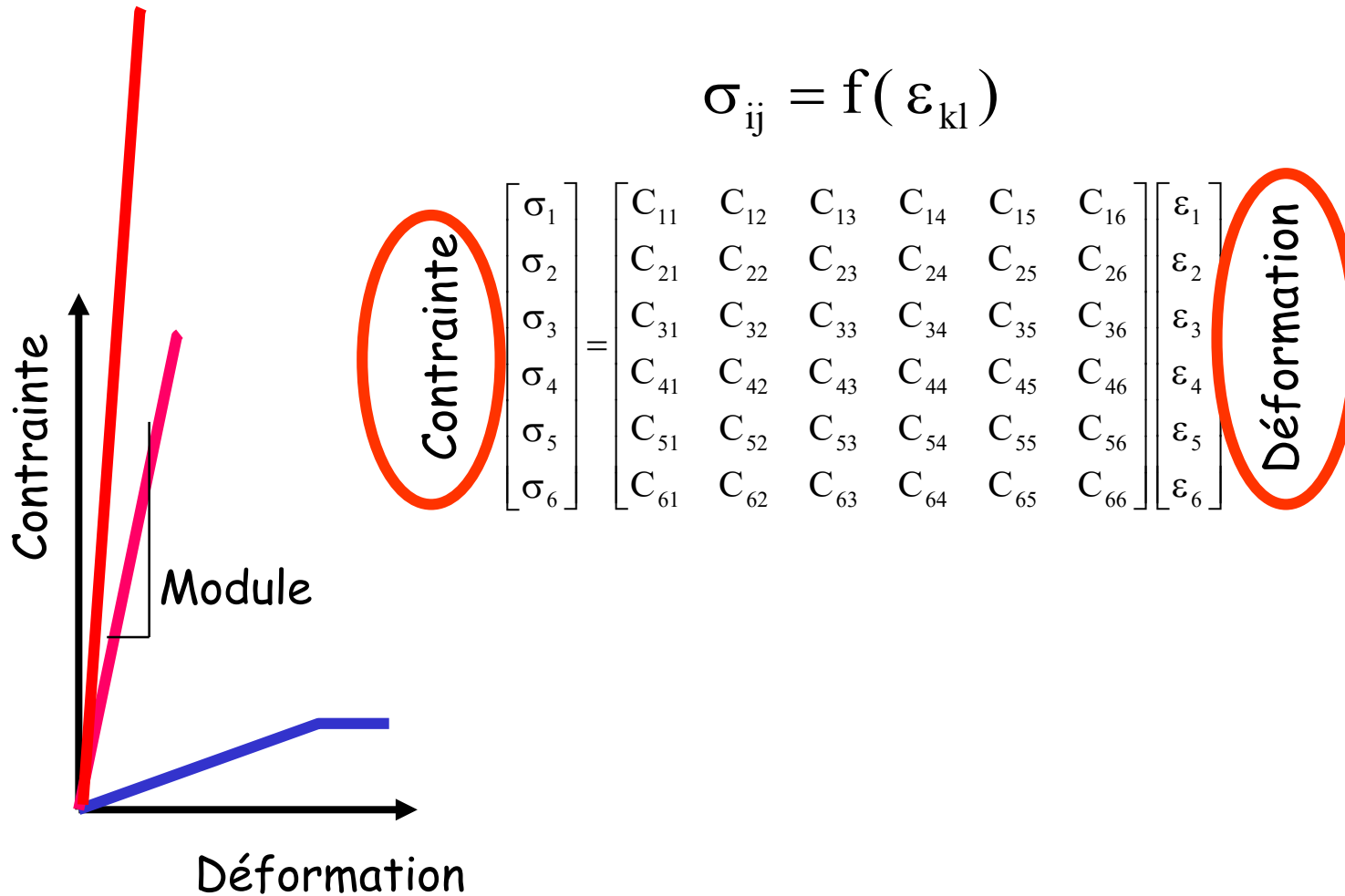
Transversalement isotrope

5 cstes

Isotrope

2 cstes

# Propriétés élastiques



$$\sigma_{ij} = f(\varepsilon_{kl})$$

$$\begin{matrix} \text{Contrainte} \\ \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \end{matrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{matrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \\ \text{Déformation} \end{matrix}$$

# Symétries des matériaux

Monocliniques (13)

Orthotropes (9)

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

Transversalement isotropes (5)  $2 \leftrightarrow 3$   $C_{22} = C_{33}$  etc

Isotropes(2)

# Constantes de l'ingénieur

$$\varepsilon_1 = \frac{\sigma_1}{E_1} \qquad \varepsilon_1 = -\nu_{21}\varepsilon_2 = -\nu_{21} \frac{\sigma_2}{E_2}$$

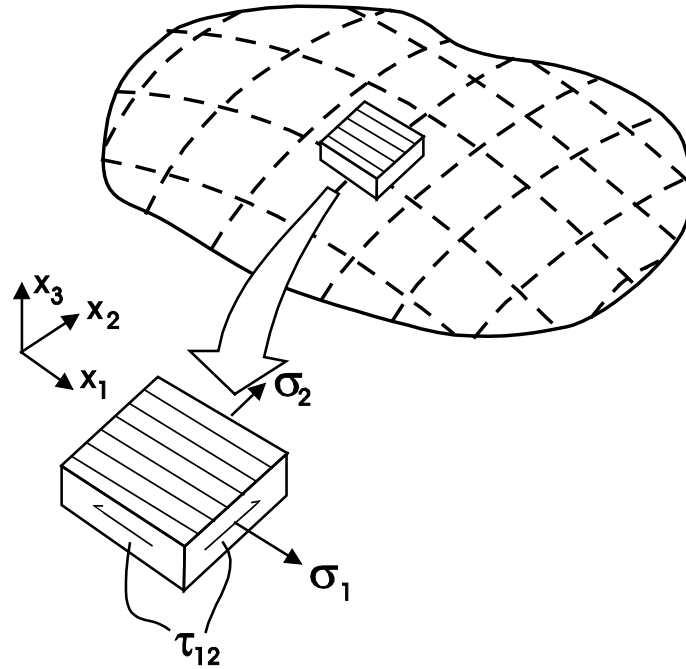
$$\{\varepsilon\} = [S]\{\sigma\}$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix}$$

$$\gamma_{12} = \frac{\tau_{12}}{G_{12}}$$

$$S_{12} = S_{21} \text{ donc } -\frac{\nu_{21}}{E_2} = -\frac{\nu_{12}}{E_1} \quad \text{pour un matériau orthotrope}$$

# Matériaux orthotropes en contraintes planes (3=0)



$$[S_{ij}] = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & 0 \\ 0 & 0 & 1/G_{12} \end{bmatrix}$$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}$$

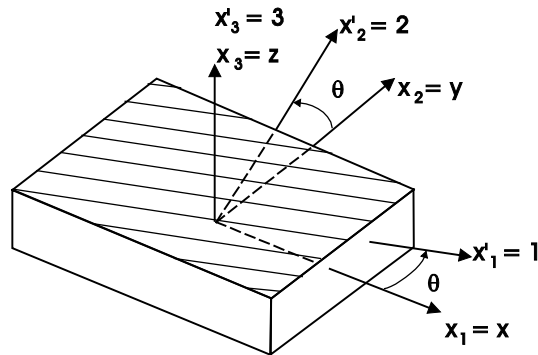
$$Q_{11} = \frac{E_1}{(1-\nu_{12}\nu_{21})}$$

$$Q_{22} = \frac{E_2}{(1-\nu_{12}\nu_{21})}$$

$$Q_{12} = \frac{\nu_{12}E_2}{(1-\nu_{12}\nu_{21})} = \frac{\nu_{21}E_1}{(1-\nu_{12}\nu_{21})}$$

$$Q_{66} = G_{12}$$

# Importance de l'orientation des fibres



$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = [T] \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

$$m = \cos, n = \sin$$

$$[T] = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2 - n^2 \end{bmatrix}$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

$$\bar{Q}_{11} = m^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + n^4 Q_{22}$$

$$\bar{Q}_{21} = \bar{Q}_{12} = m^2 n^2 (Q_{11} + Q_{22} - 4Q_{66}) + Q_{12} (m^4 + n^4)$$

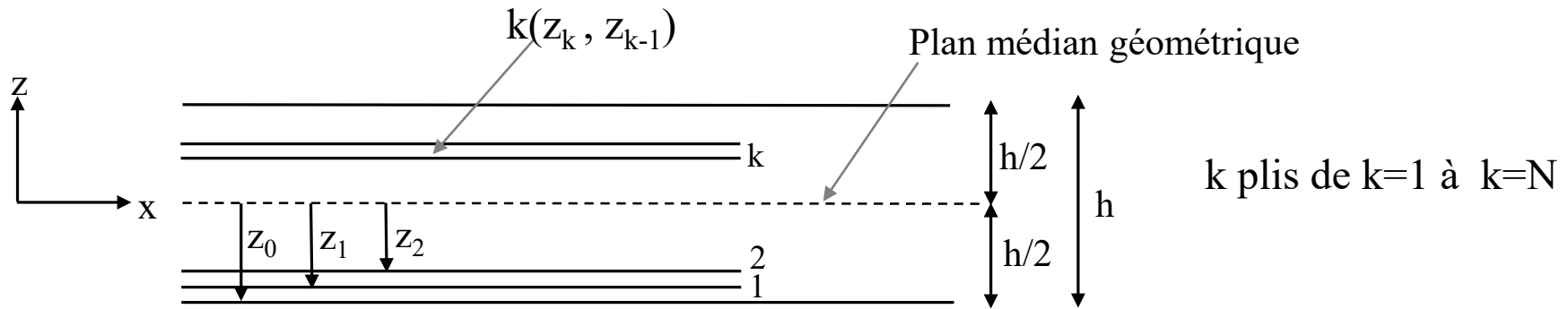
$$\bar{Q}_{22} = n^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + m^4 Q_{22}$$

$$\bar{Q}_{16} = m^3 n (Q_{11} - Q_{12}) + mn^3 (Q_{12} - Q_{22}) - 2mn(m^2 - n^2) Q_{66}$$

$$\bar{Q}_{26} = mn^3 (Q_{11} - Q_{12}) + m^3 n (Q_{12} - Q_{22}) + 2mn(m^2 - n^2) Q_{66}$$

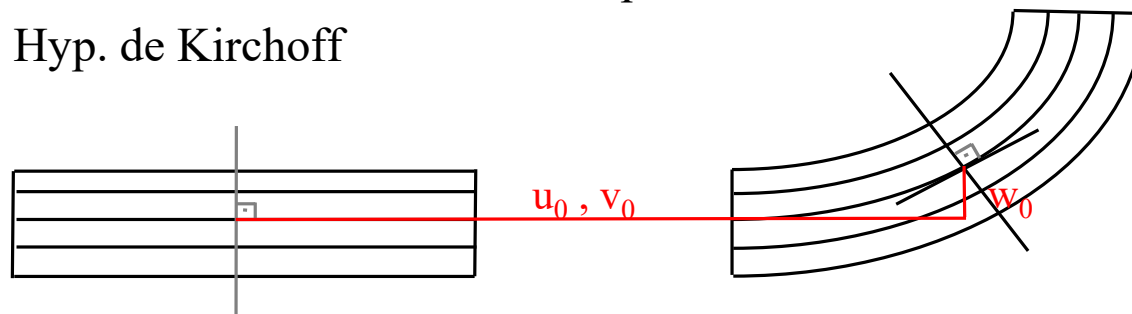
$$\bar{Q}_{66} = m^2 n^2 (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) + (m^4 + n^4) Q_{66}$$

# Elasticité des stratifiés



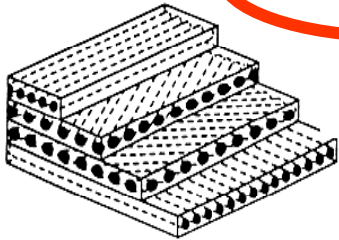
## (H) CLT: Classical Laminate Theory

- Linéaire élastique  $\varepsilon_x$
- Orthotrope
- Membrane, contraintes planes ( $\sigma_3, \varepsilon_3 = 0$ )  $\equiv$  pas de déformation selon l'axe  $z$ , seulement déformation hors du plan
- Hyp. de Kirchoff

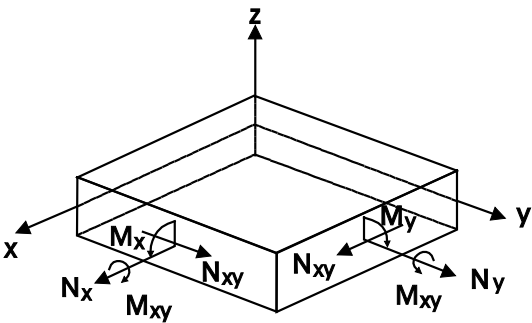
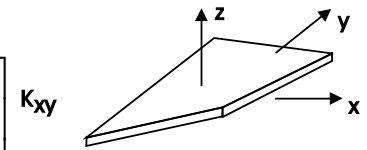
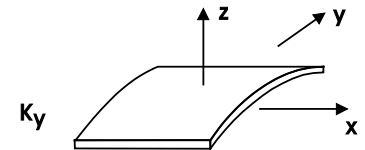
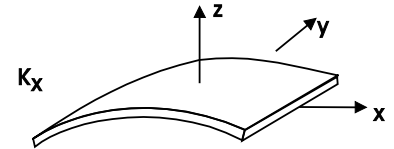


# Elasticité des stratifiés, k couches

k strates



$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix}$$



$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

$$A_{ij} = \sum_{k=1}^N (\overline{Q_{ij}})_k (z_k - z_{k-1})$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^N (\overline{Q_{ij}})_k (z_k^2 - z_{k-1}^2)$$

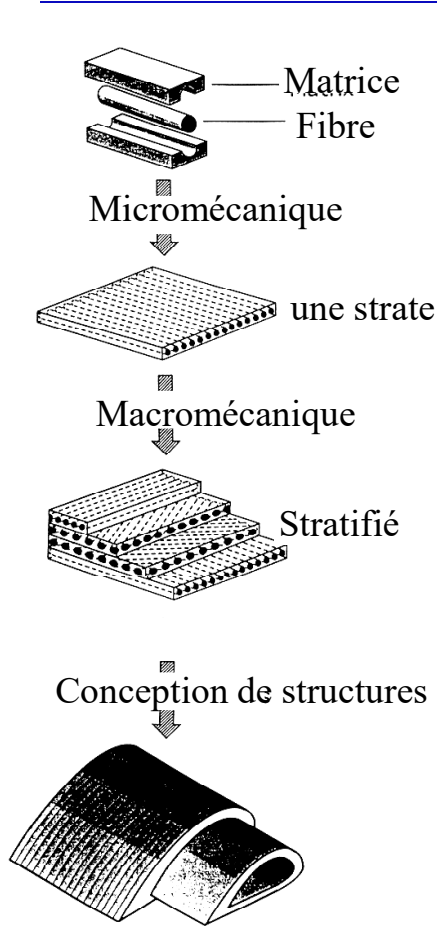
$$D_{ij} = \frac{1}{3} \sum_{k=1}^N (\overline{Q_{ij}})_k (z_k^3 - z_{k-1}^3)$$

# Couplages

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

# De la fibre à la structure



$$E_1 = E_f V_f + E_m (1 - V_f)$$

$$Q_{11} = \frac{E_1}{(1 - \nu_{12}\nu_{21})}$$

$$\bar{Q}_{11} = m^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + n^4 Q_{22}$$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \quad \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

$$A_{ij} = \sum_{k=1}^N (\bar{Q}_{ij})_k (z_k - z_{k-1})$$

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{12} & a_{22} & 0 \\ 0 & 0 & a_{66} \end{bmatrix} \left\{ \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} + \begin{bmatrix} N_x^T \\ N_y^T \\ 0 \end{bmatrix} \right\}$$

$$E_x = \frac{A_{11}A_{22} - A_{12}^2}{h A_{22}}$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & 0 \\ -\frac{\nu_{yx}}{E_y} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

Mx élastiques  
Porosité nulle/minimale  
Interfaces fibre-matrice parfaites/optimales

Orientations des fibres, m, n

Orthotropie  
Contraintes planes

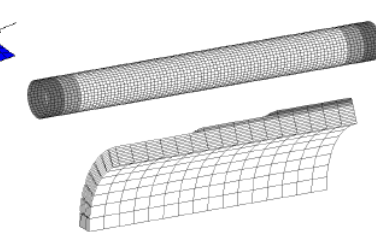
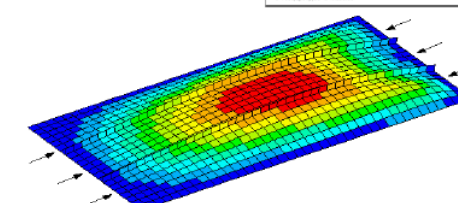
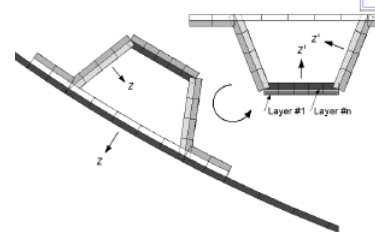
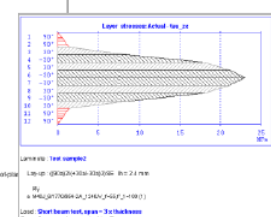
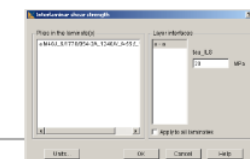
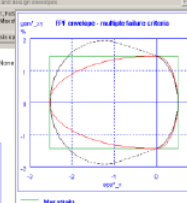
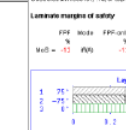
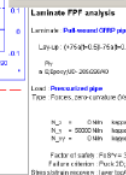
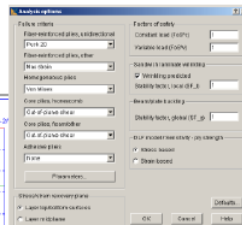
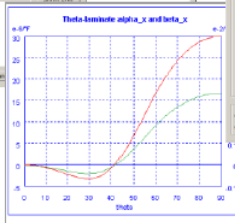
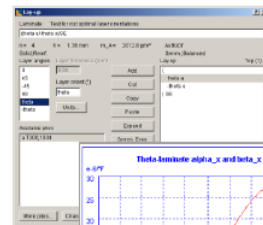
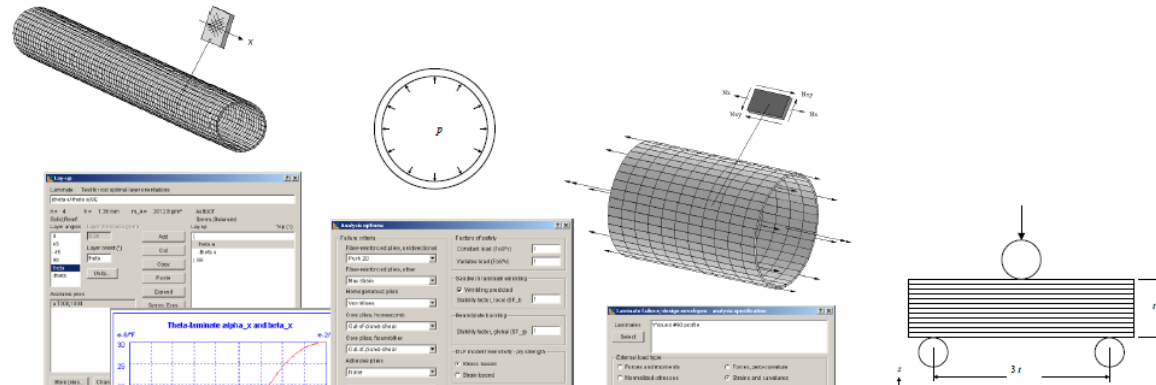
Adhésion entre plis parfaite/optimale

Symétries d'empilement  
Effets de couplage

Cas de charges  
Propriétés effectives  
Mécanique des matériaux

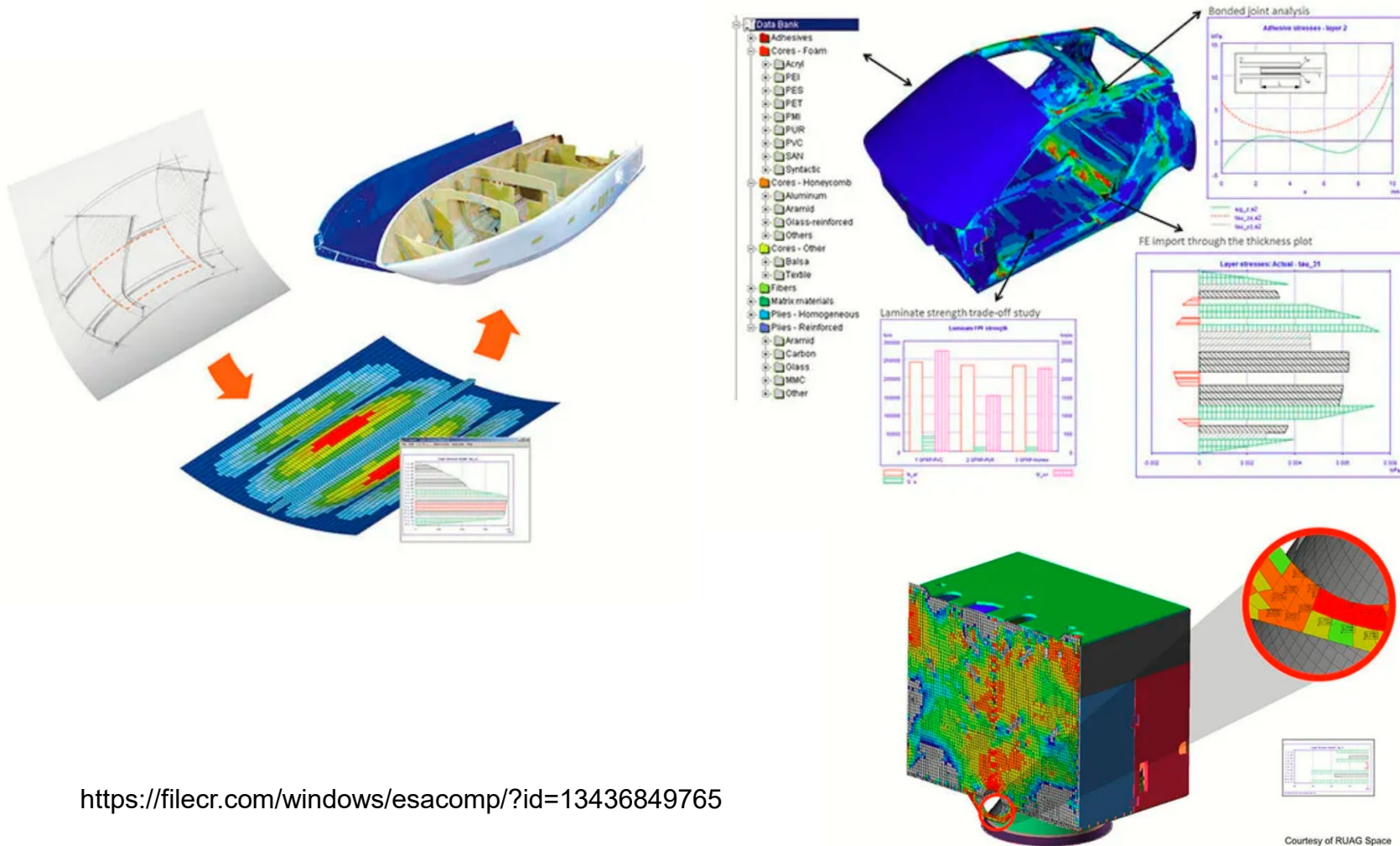


# Mécanique des composites stratifiés



<https://www.altair.com/composites/>

# FEM



<https://filecr.com/windows/esacomp/?id=13436849765>

Courtesy of RUAG Space

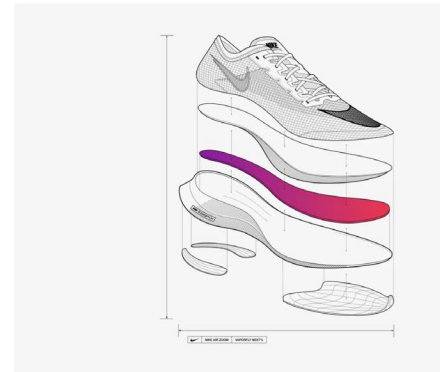
# Elasticité des stratifiés



<https://www.ouest-france.fr/sport/athletisme/championnats-du-monde/mondiaux-d-athletisme-saut-la-perche-valentin-lavillenie-sixeme-de-la-finale-6545575>

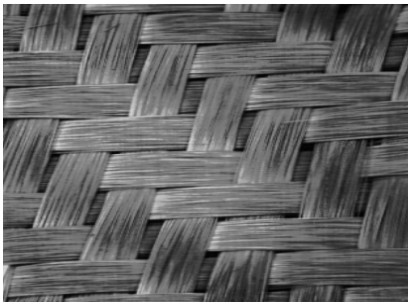


<https://sportinnov.wordpress.com/2014/11/21/les-protheses-flex-foot-cheetah-quand-lhomme-et-la-technologie-ne-font-quun/>

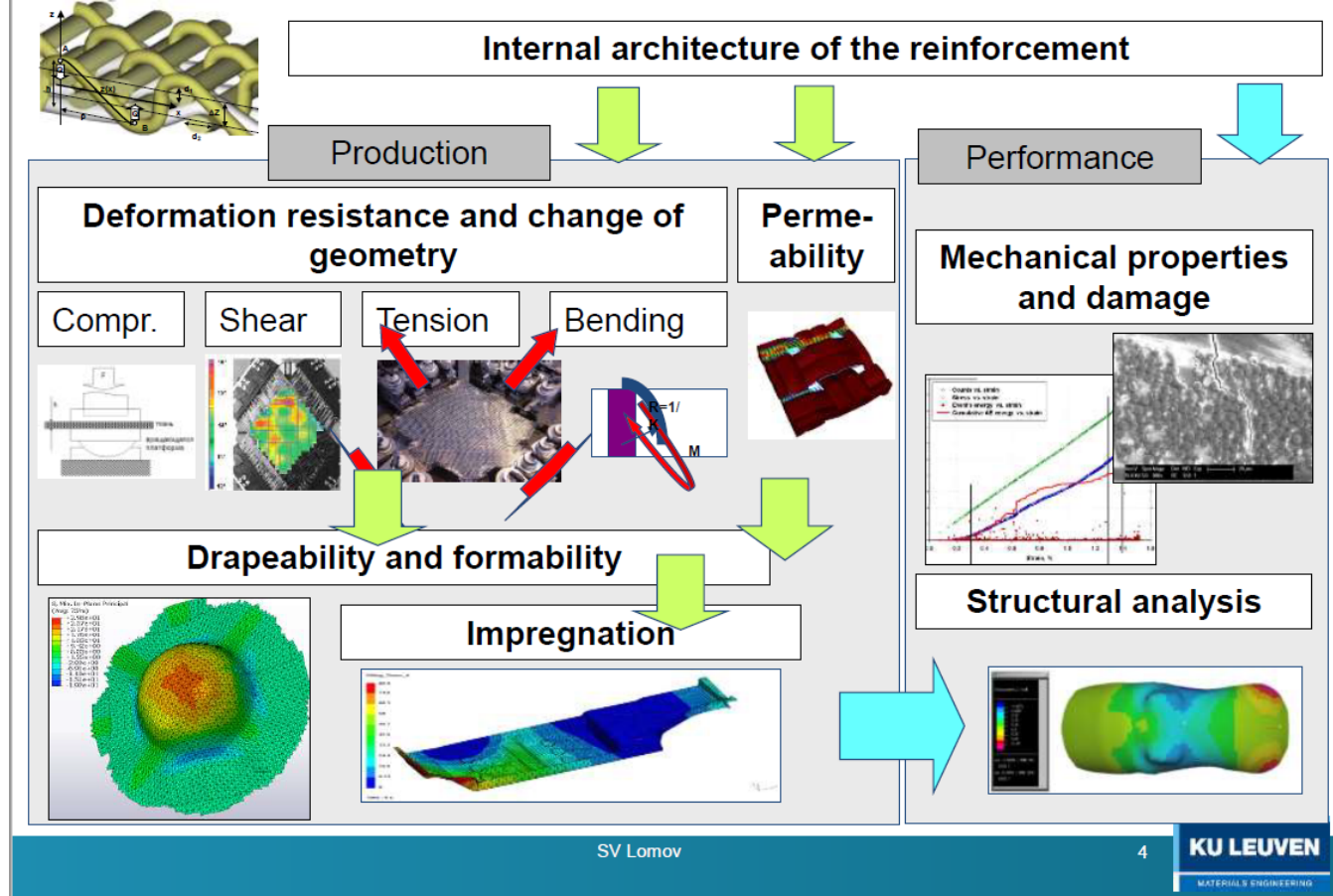


<https://www.nike.com/fr/running/vaporfly>

# Les composites textiles

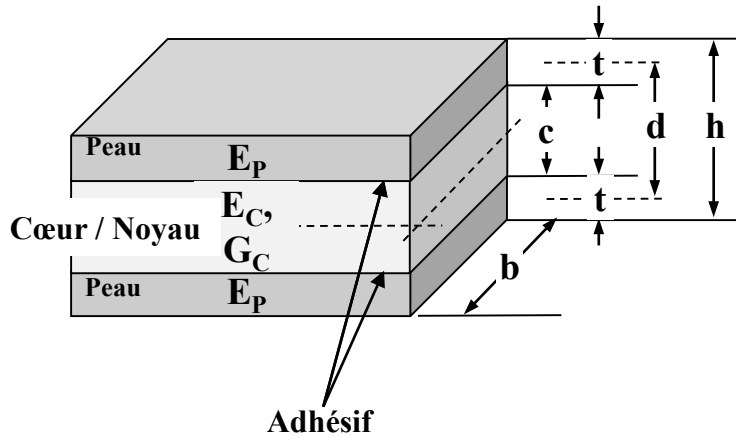
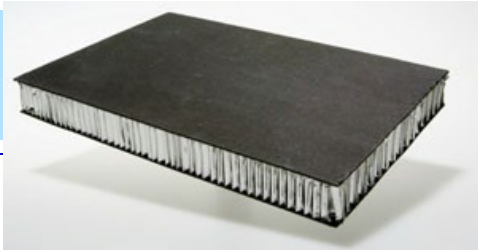


## Integrated Design Tool: textile composites



<https://www.mtm.kuleuven.be/onderzoek/scalint/Composites/software/wisetex>

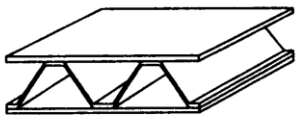
# Les structures sandwich



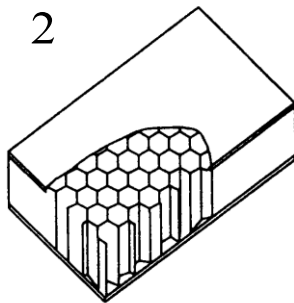
Peaux			
	$\rho$ [kg/m <sup>3</sup> ]	E [GPa]	$\sigma$ [MPa]
<b>Métal</b>	2700-8000	70-210	200-1000
<b>Bois</b>	~500	~12	20-40
<b>Composites UD</b>	~1600	40-200	1000-1200
<b>Composites bi-directionnels</b>	~1600	15-100	200-800
<b>Mats</b>	~1700	~10	80-150

Âme/ Cœur Noyau		
	$\rho$ [kg/m <sup>3</sup> ]	$\tau$ [MPa]
<b>Nid d'abeilles (Al/ Nomex/TP)</b>	20-100	0.2-2
<b>Balsa</b>	150	2
<b>Mousse</b>	15-80	0.2-3

$$\text{Rigidité} \approx E_P \frac{b t d^2}{2}$$



Corrugated



Honeycomb

+ Adhésifs

# Applications

Aérospatiale  
Aéronautique  
Sport (skis, planches à voiles, F1 )  
Ferrovière



 **econcore**  
economic core technologies

