

Synthèse sur les Matériaux Composites

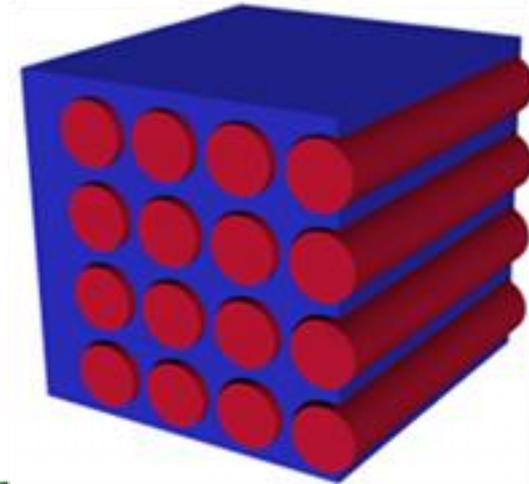
L.Guillaumat - S.Terekhina



1 Matériaux composites : concept



1.1 Le concept

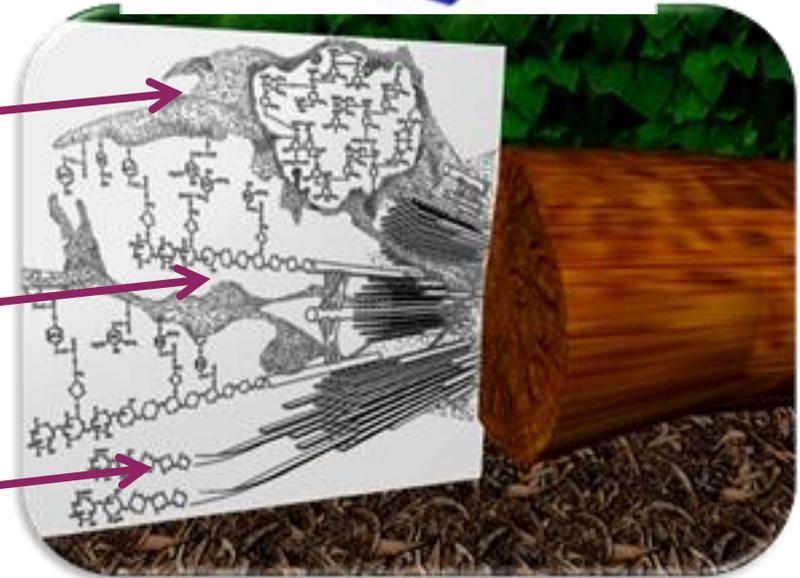


Constituants ?

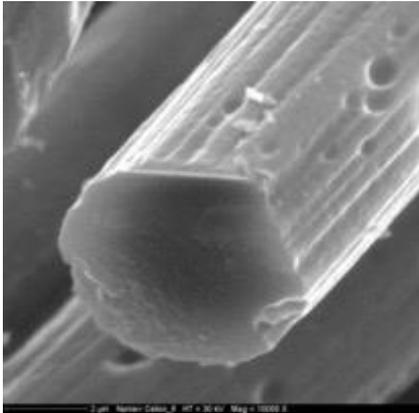
Matrice

Interphase

Fibres



Fibre carbone



Fibre verre



Fibre Kevlar



Lin



1.3 La matrice

Trois familles de matrice

Polymère : polyester,
époxyde, phénolique, ...



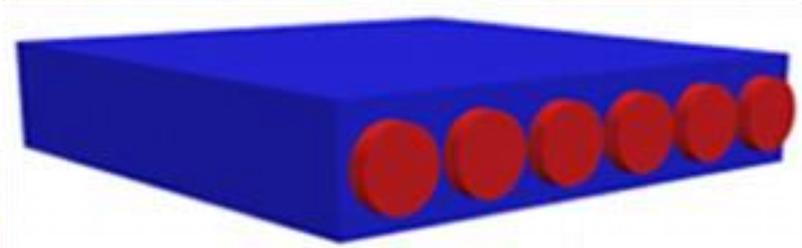
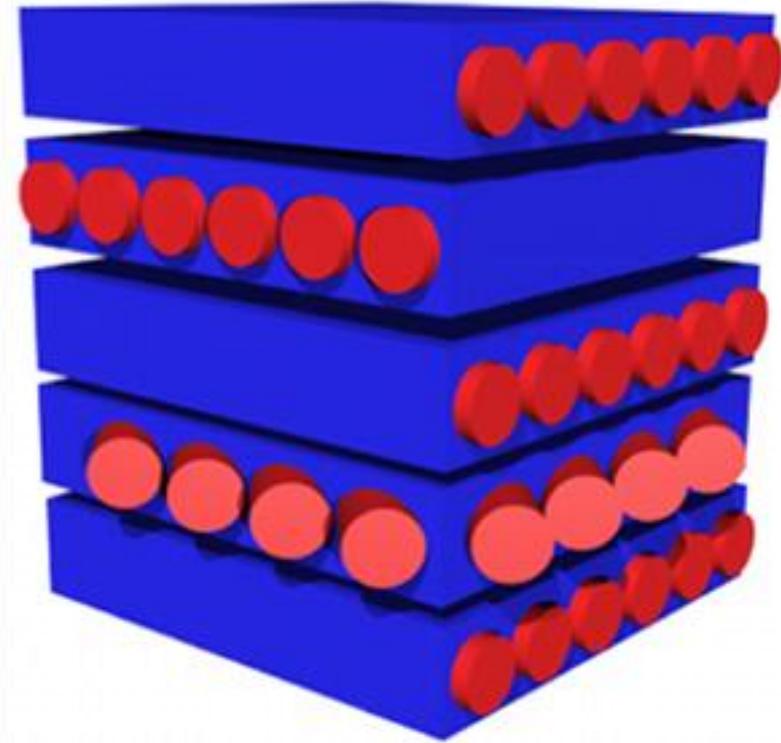
Métal : aluminium,
titane



Céramique : Sic, C

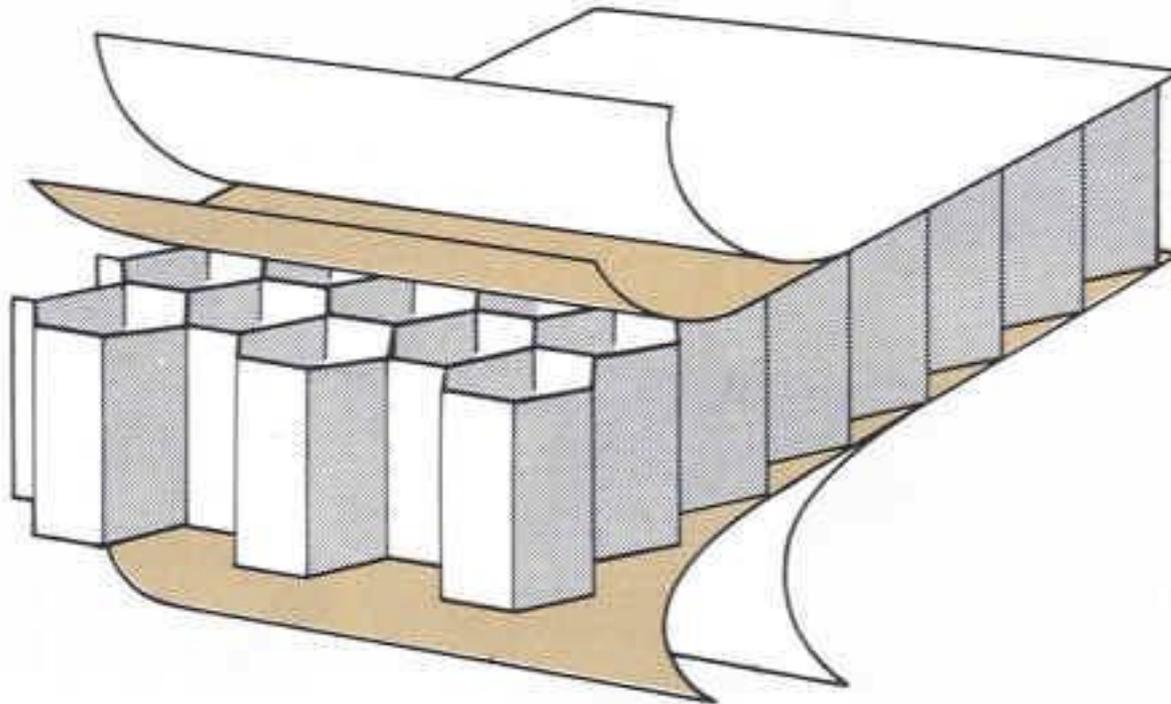


Matériaux stratifiés



Superposition de plis
Quelques règles à respecter

Les Sandwichs

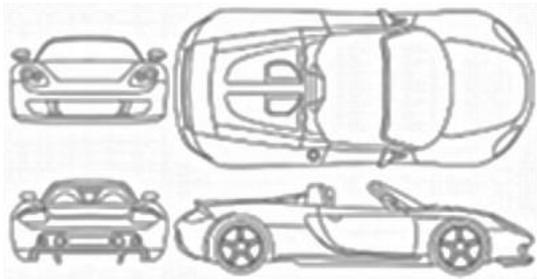


2 Les procédés



2.1 Le moulage au contact

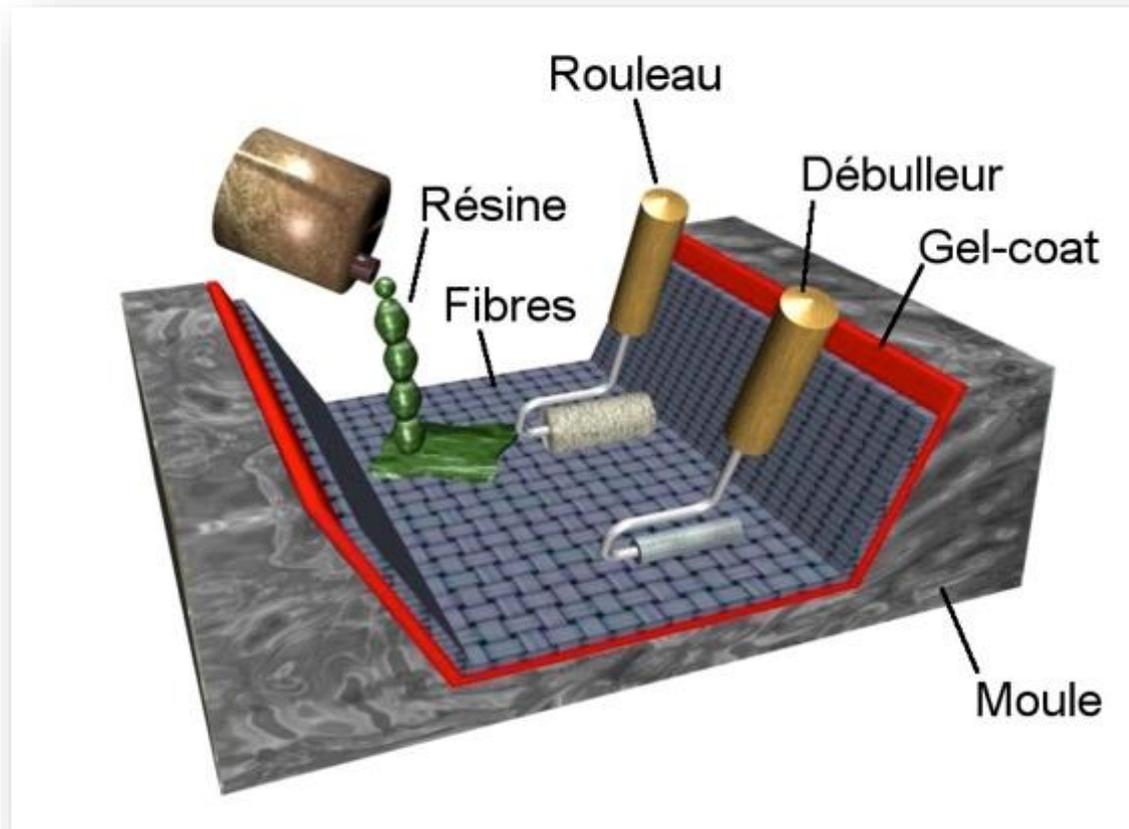
Modèle numérique
Blue print



Modèle

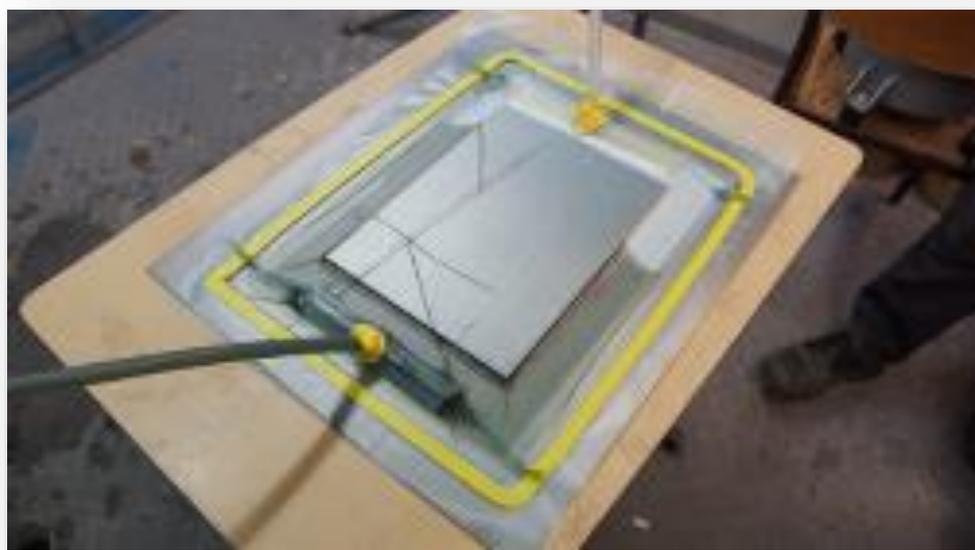
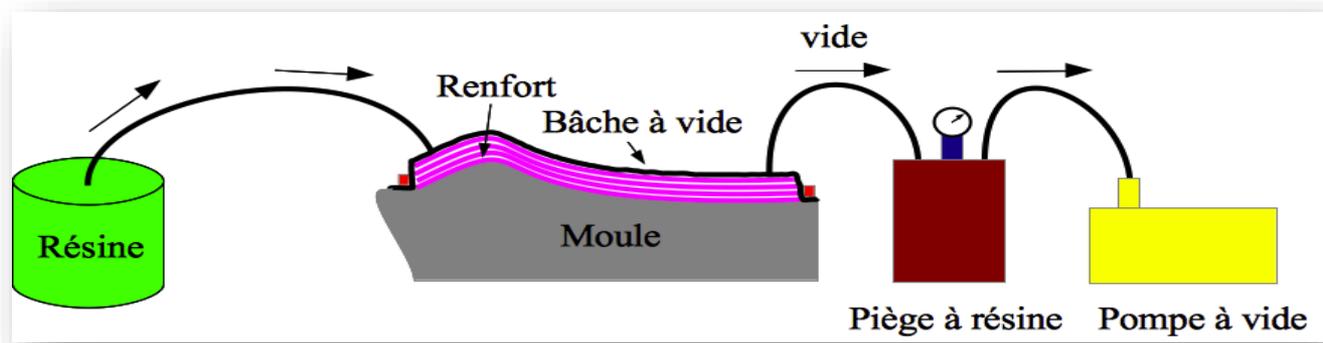


2.1 Le moulage au contact



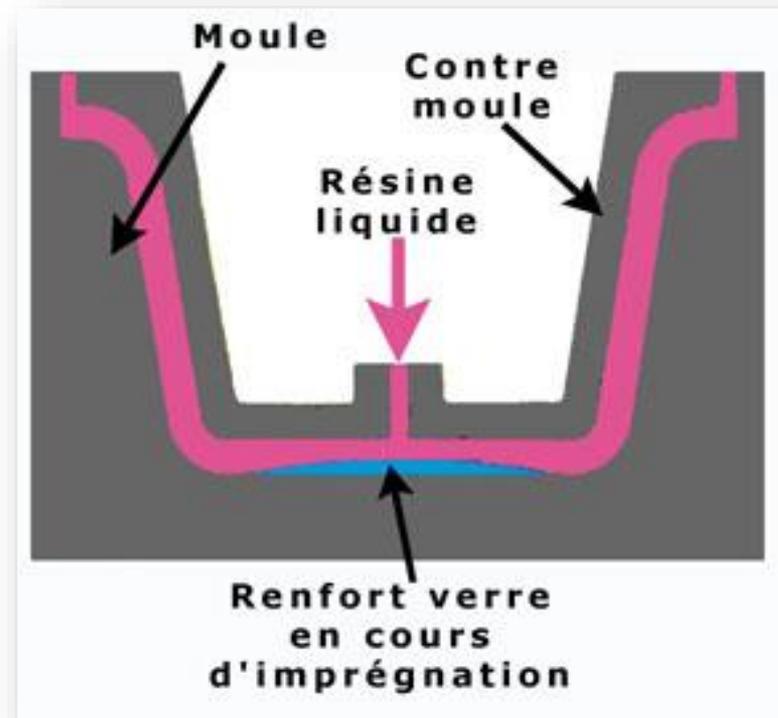
2.2 L'infusion

Evolution du procédé précédent
Toute l'opération se réalise sous vide.





Resin Transfert Molding



Réglage Température et Pression

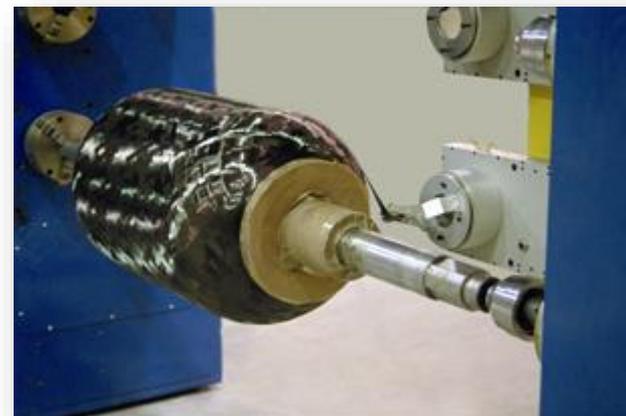
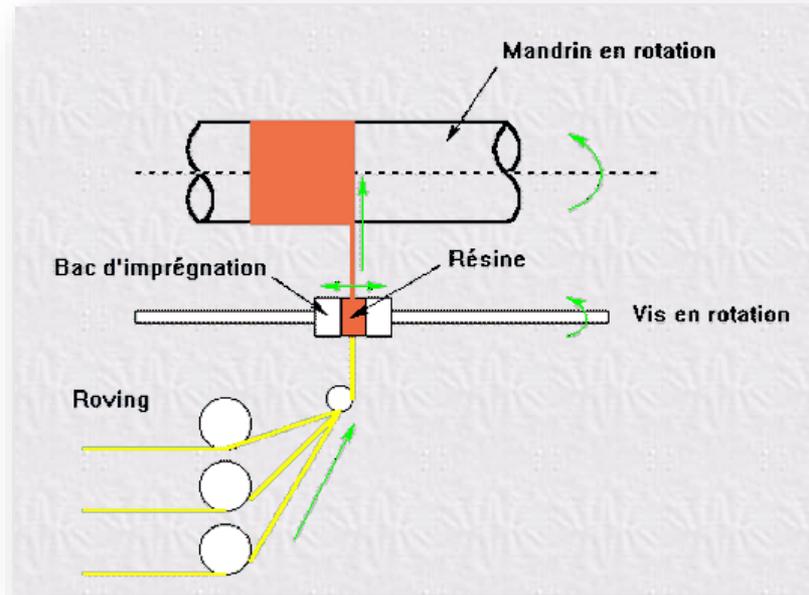


Préimprégnés

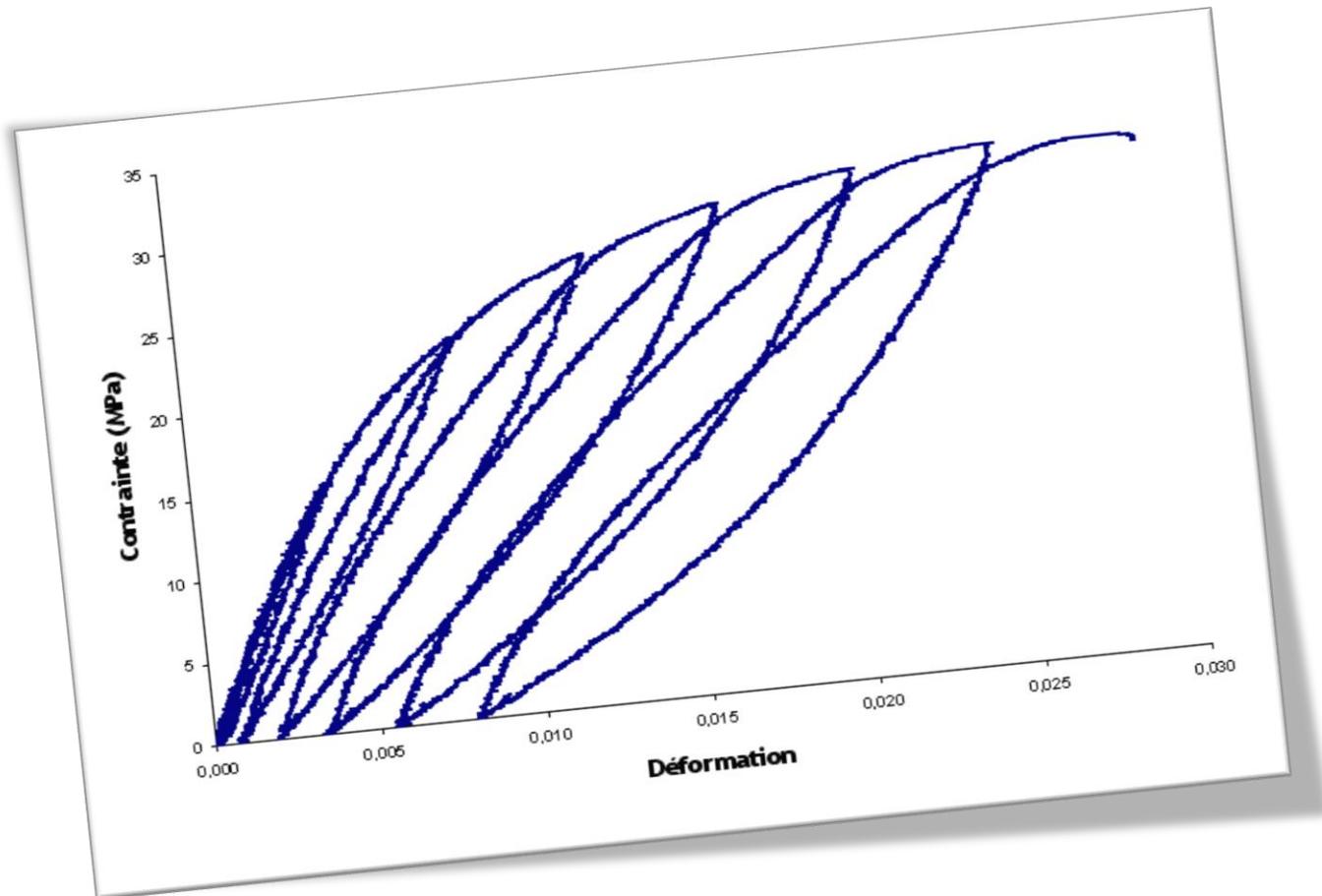


Pièces de très haute qualité

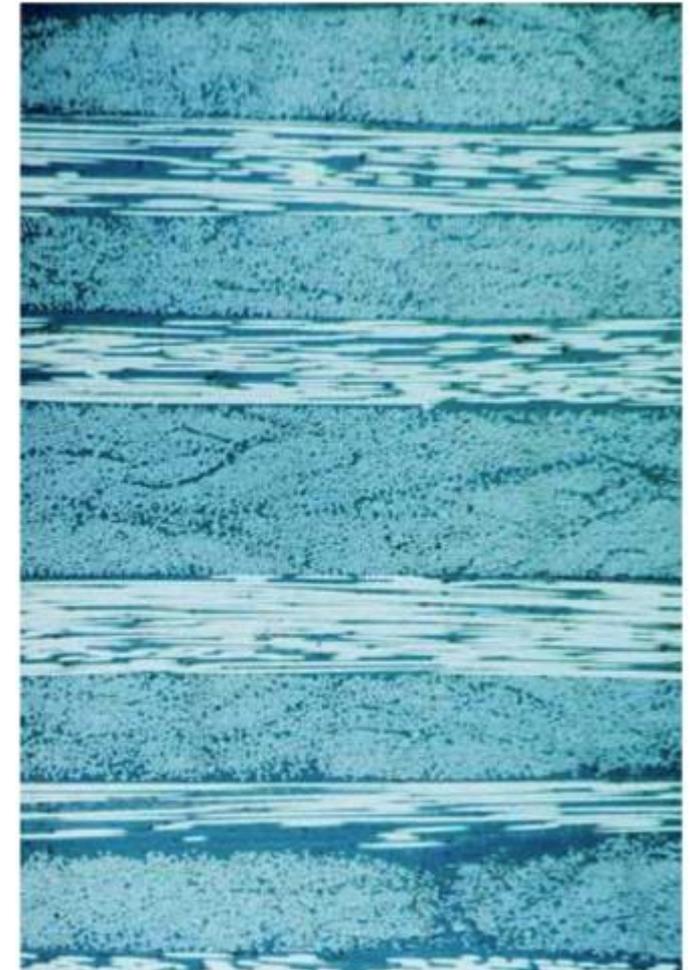
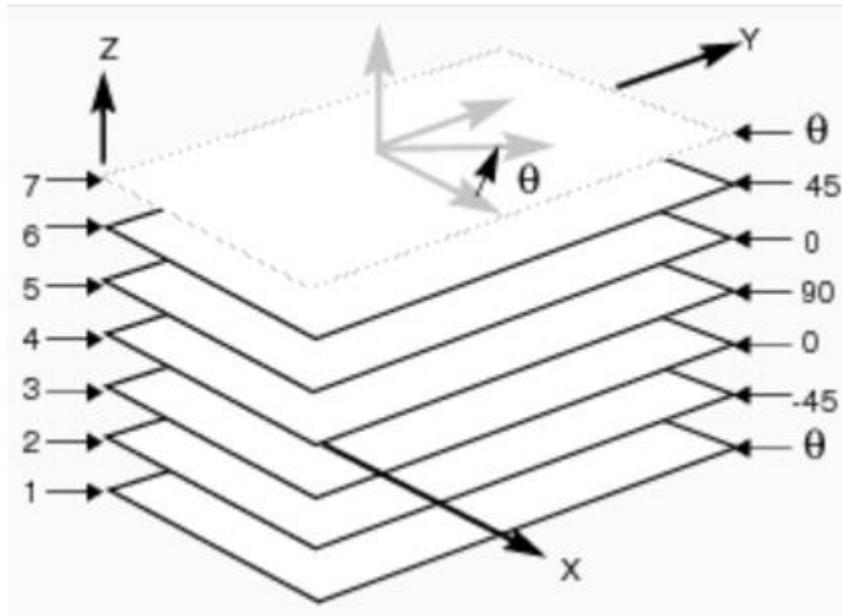
Pièces de révolution



3 Comportements mécaniques du pli



Construction d'un empilement de plusieurs pli : stratifié



⇒ Calculs analytiques et/ou numériques

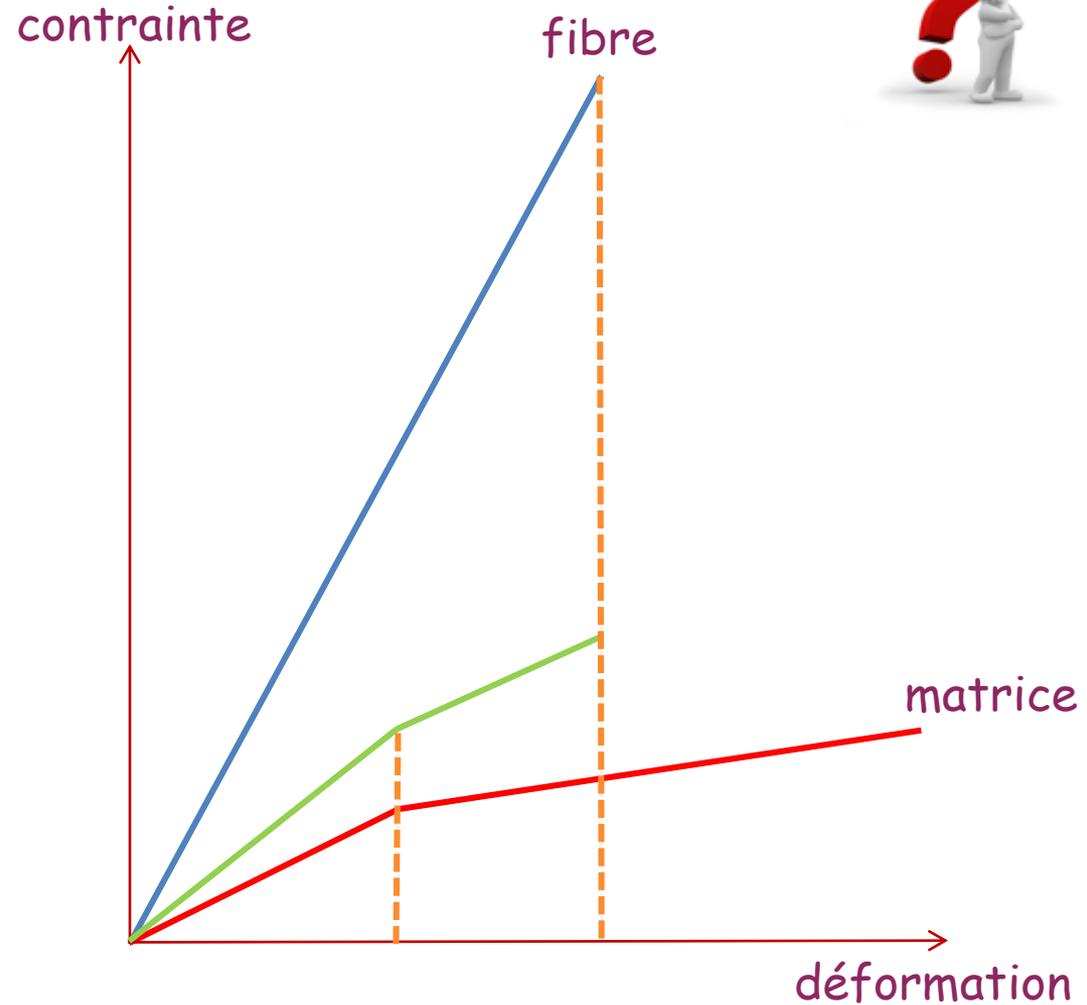
Besoin obtenir la loi de comportement de l'empilement ?

Composite unidirectionnel

Loi des mélanges

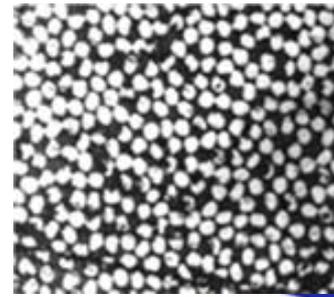
$$E_c = E_f V_f + E_m V_m$$

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

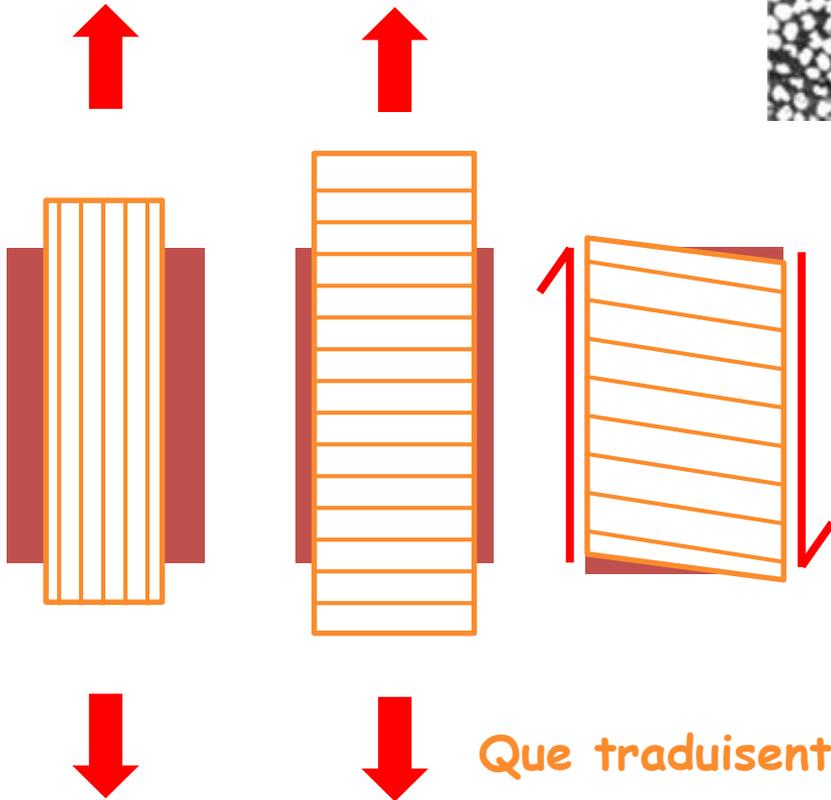
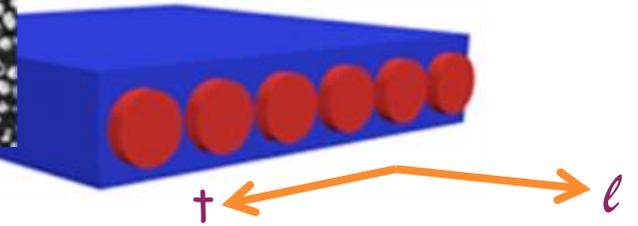


3.3 Comportement du pli

Le pli : brique élémentaire du stratifié



Repère du matériau



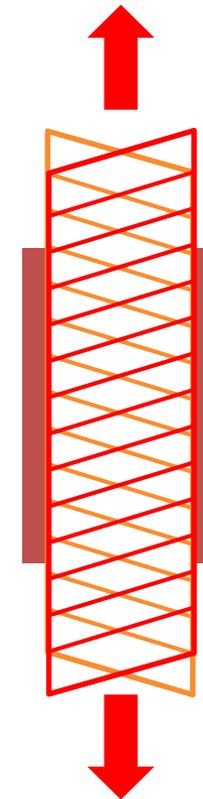
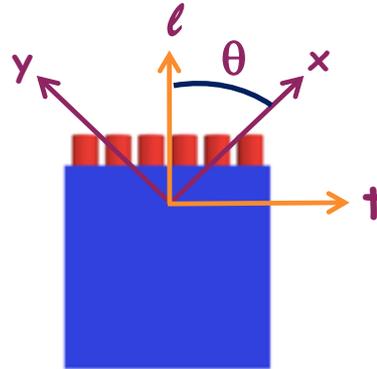
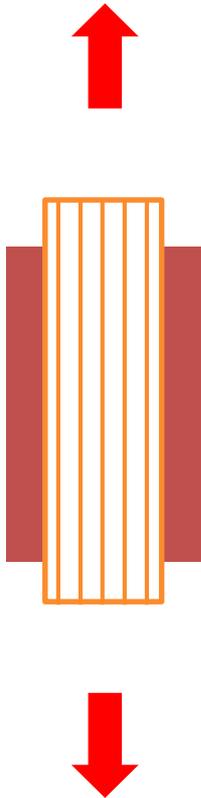
Notion d'anisotropie

$$\begin{Bmatrix} \varepsilon_\ell \\ \varepsilon_t \\ \varepsilon_{\ell t} \end{Bmatrix} = \begin{bmatrix} S_{\ell\ell} & S_{\ell t} & 0 \\ S_{t\ell} & S_{tt} & 0 \\ 0 & 0 & S_{ss} \end{bmatrix}_{\{\ell;t\}} \begin{Bmatrix} \sigma_\ell \\ \sigma_t \\ \sigma_{\ell t} \end{Bmatrix}$$

Que traduisent physiquement les zéros dans la matrice ?

Essai hors axes des fibres :

$$\begin{Bmatrix} \varepsilon_\ell \\ \varepsilon_t \\ \varepsilon_{\ell t} \end{Bmatrix} = \begin{bmatrix} S_{\ell\ell} & S_{\ell t} & 0 \\ S_{t\ell} & S_{tt} & 0 \\ 0 & 0 & S_{ss} \end{bmatrix}_{\{\ell;t\}} \begin{Bmatrix} \sigma_\ell \\ \sigma_t \\ \sigma_{\ell t} \end{Bmatrix}$$



- 1) Que se passe t-il dans ce cas ?
- 2) Comment annuler cet effet ?

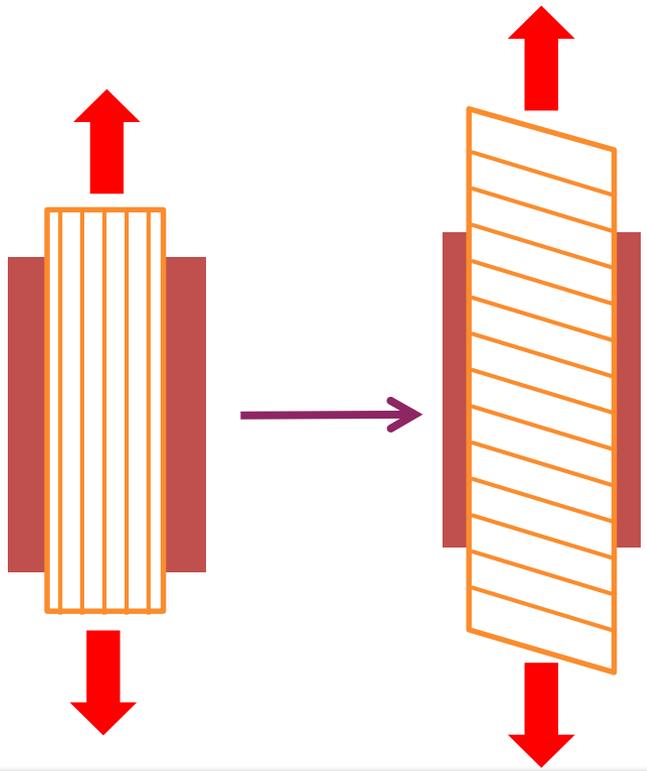


3.3 Comportement du pli

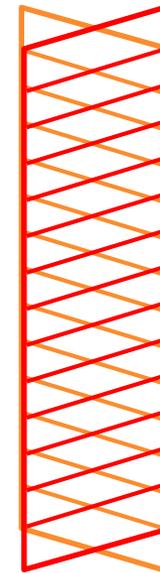


Apparition de couplages : traction - compression / cisaillement

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} & S_{xs} \\ S_{yx} & S_{yy} & S_{ys} \\ S_{rx} & S_{ry} & S_{rr} \end{bmatrix}_{\{x;y\}} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix}$$

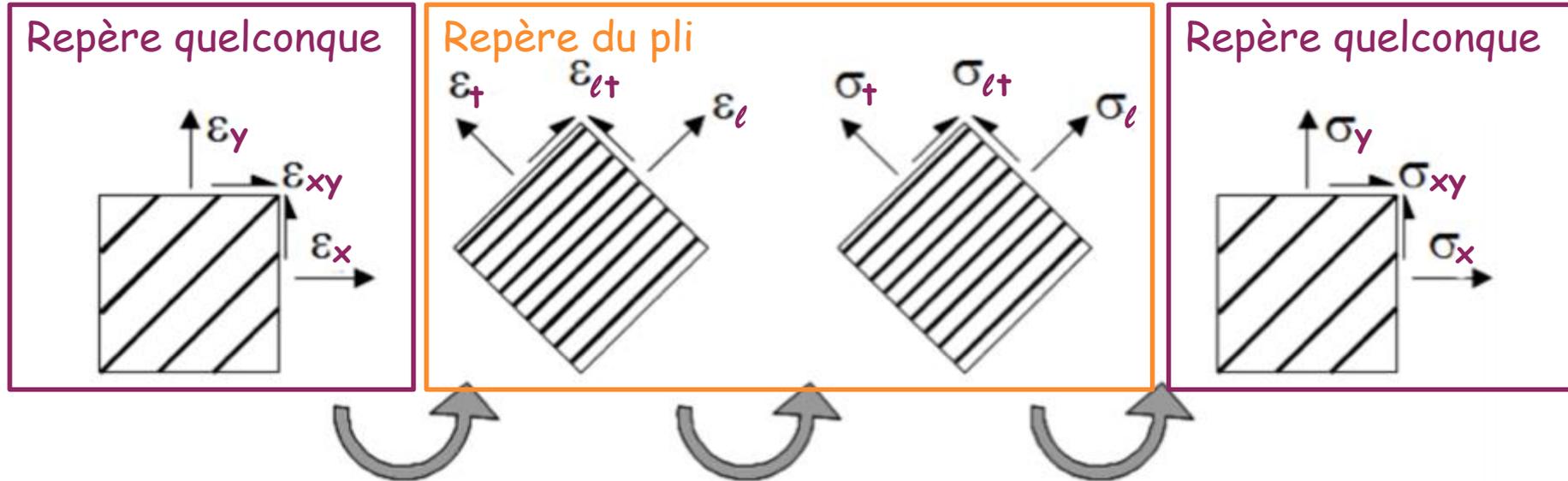


Annulation du couplage => ± θ



3.3 Comportement du pli

Le pli : exprimé dans un repère quelconque



$$\begin{bmatrix} c^2 & s^2 & -2c.s \\ s^2 & c^2 & 2c.s \\ c.s & -c.s & c^2 - s^2 \end{bmatrix} \begin{bmatrix} Q_{\ell\ell} & Q_{\ell t} & 0 \\ Q_{t\ell} & Q_{tt} & 0 \\ 0 & 0 & Q_{ss} \end{bmatrix}_{\{\ell;t\}} \begin{bmatrix} c^2 & s^2 & c.s \\ s^2 & c^2 & -c.s \\ -2c.s & 2c.s & c^2 - s^2 \end{bmatrix}$$

Avec :
 $c = \cos(\theta)$ et $s = \sin(\theta)$

3.3 Comportement du pli

Loi de comportement : repère quelconque



	Q_{ll}	Q_{tt}	Q_{tl}	Q_{ss}
Q_{xx}	C^4	S^4	$2C^2S^2$	$4C^2S^2$
Q_{yy}	S^4	C^4	$2C^2S^2$	$4C^2S^2$
Q_{xy}	C^2S^2	C^2S^2	C^4+S^4	$-4C^2S^2$
Q_{rr}	C^2S^2	C^2S^2	$-2C^2S^2$	$(C^2-S^2)^2$
Q_{xr}	C^3S	$-CS^3$	CS^3-C^3S	$2(CS^3-C^3S)$
Q_{yr}	CS^3	$-C^3S$	C^3S-CS^3	$2(C^3S-CS^3)$

Exemple : $Q_{xx} = C^4 \cdot Q_{ll} + S^4 \cdot Q_{tt} + 2C^2S^2 Q_{lt} + 4C^2S^2 Q_{ss}$

A noter que les termes de 2 lignes de ce tableau ont une propriété mathématique différente des autres. Lesquelles et pourquoi?

3.3 Comportement du pli



Composite unidirectionnel

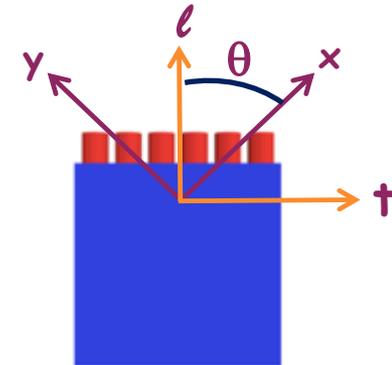
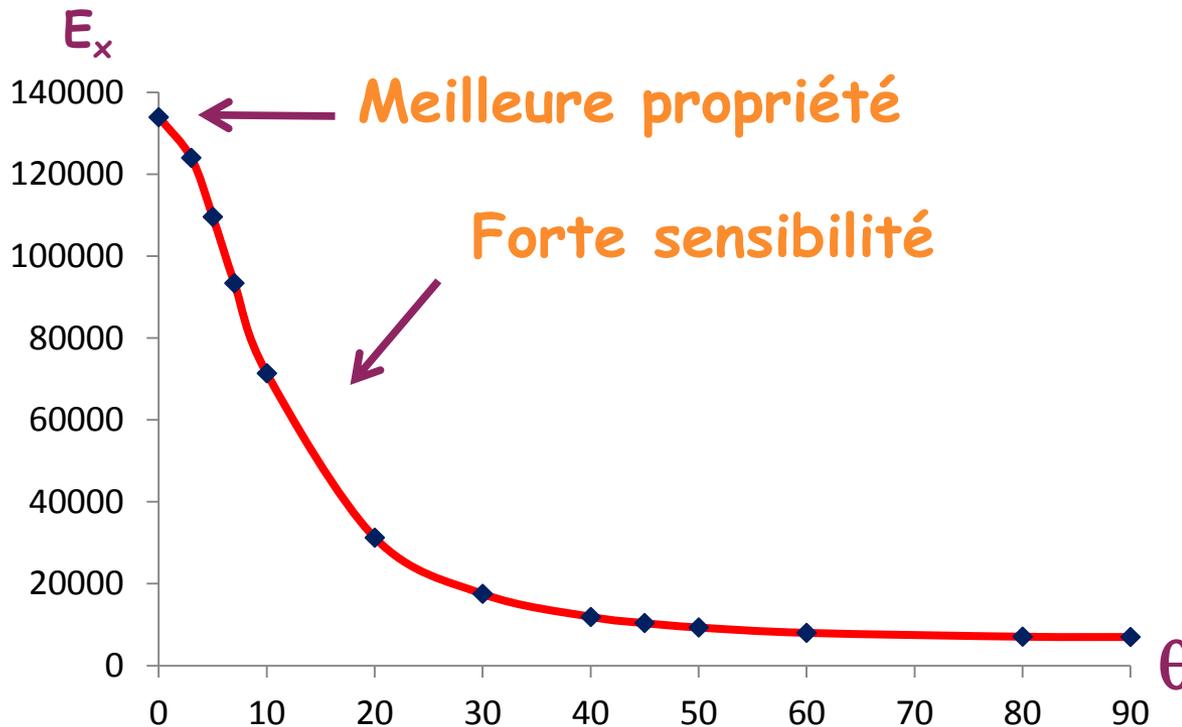
$$E_\ell = 134000\text{Mpa}$$

$$E_t = 7000\text{Mpa}$$

$$G_{\ell t} = 4200\text{Mpa}$$

$$\nu_{t\ell} = 0,013$$

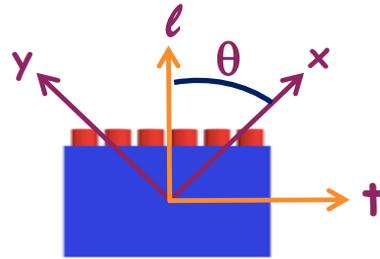
$$E_x = \frac{1}{\frac{c^4}{E_\ell} + \frac{s^4}{E_t} + 2c^2s^2 \left(\frac{1}{2G_{\ell t}} - \frac{\nu_{\ell t}}{E_\ell} \right)}$$



3.3 Comportement du pli

Composite unidirectionnel

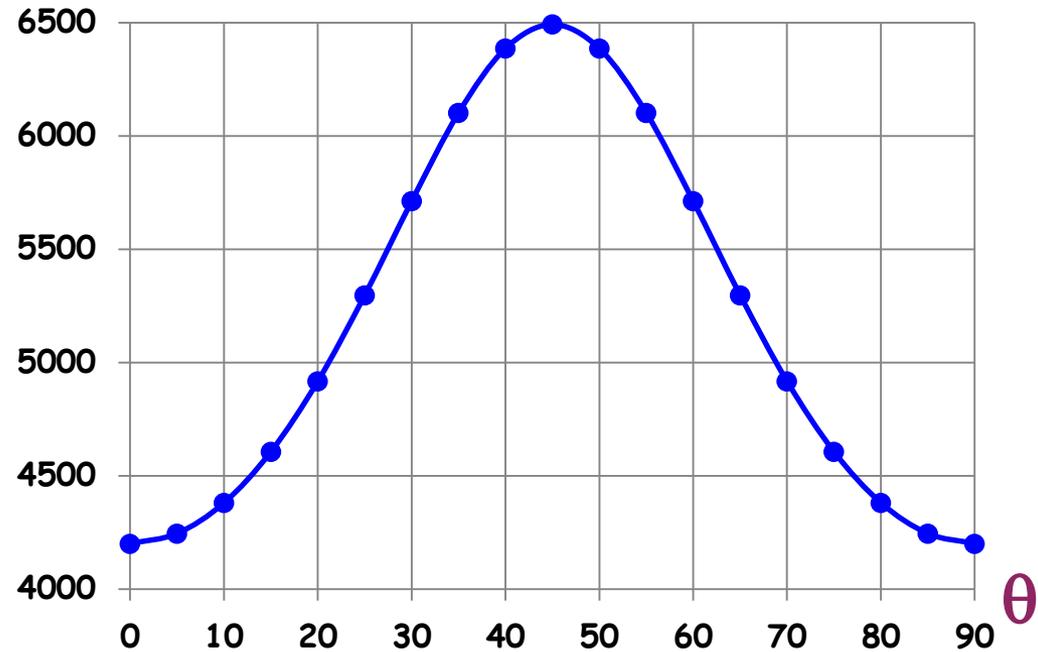
$E_l = 134000\text{Mpa}$
 $E_t = 7000\text{Mpa}$
 $G_{\ell t} = 4200\text{Mpa}$
 $\nu_{t\ell} = 0,013$



$$G_{xy}(\theta) = \frac{1}{4c^2s^2 \left(\frac{1}{E_l} + \frac{1}{E_t} + 2 \frac{\nu_{t\ell}}{E_t} \right) + \frac{(c^2 - s^2)^2}{G_{\ell t}}}$$



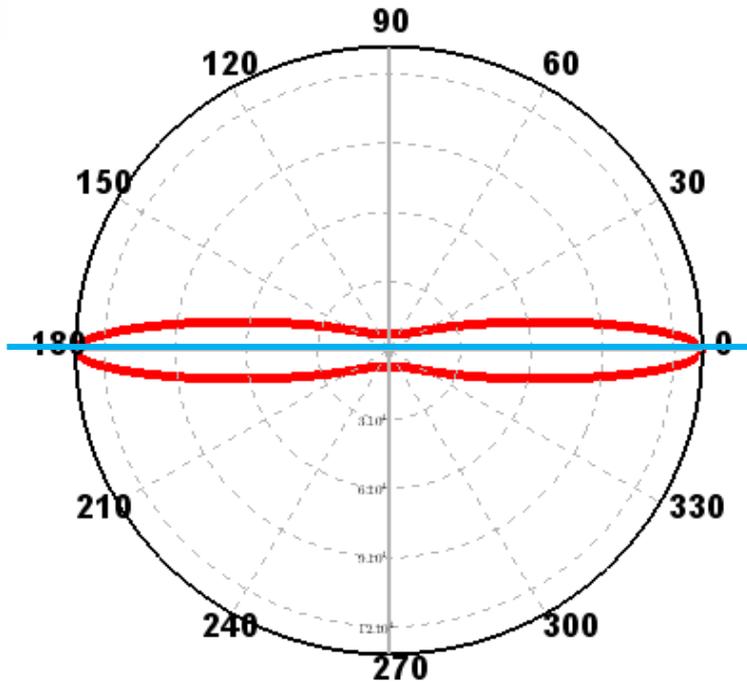
Pourquoi le module de cisaillement est maximum à 45° ?



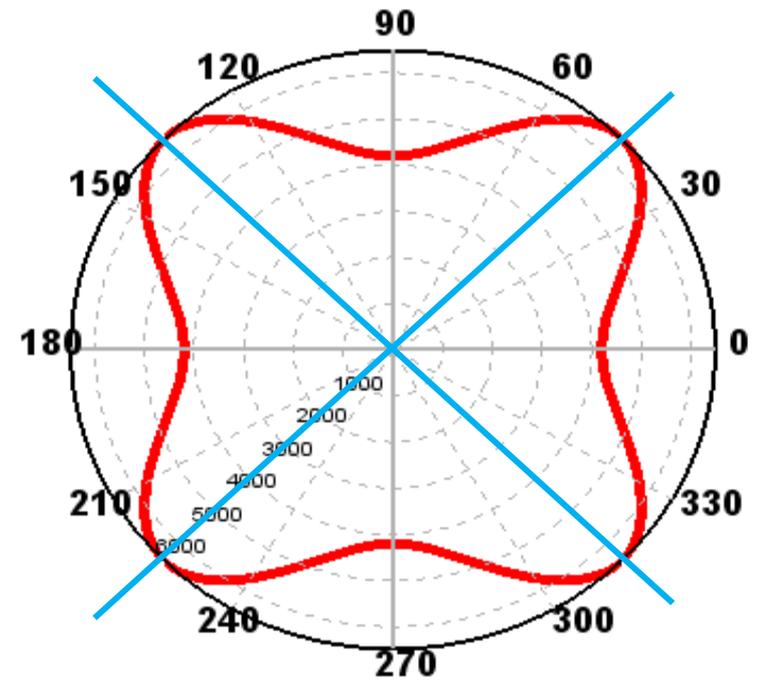
3.3 Comportement du pli

Représentation polaire de :

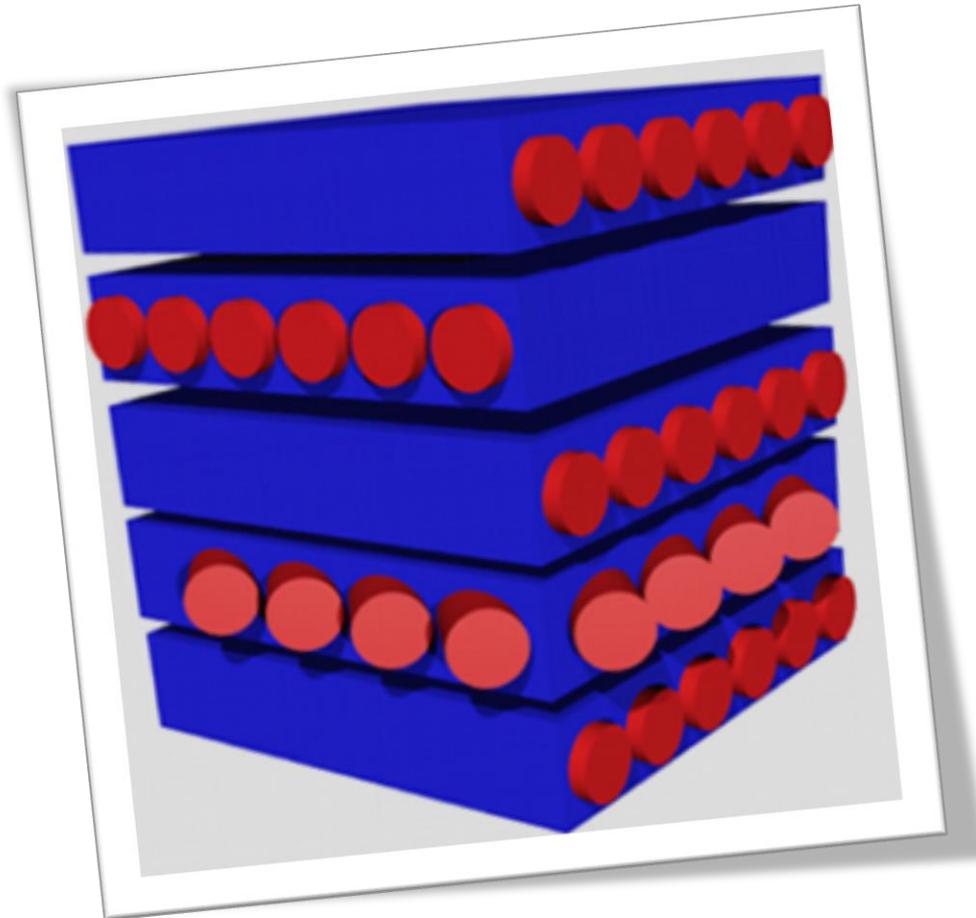
E_x pour un UD (0°)



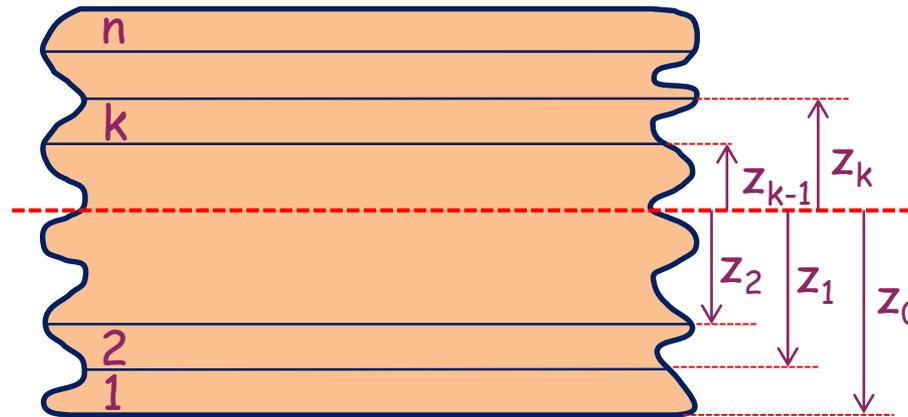
E_x pour un $\pm 45^\circ$



4 Théorie des stratifiés



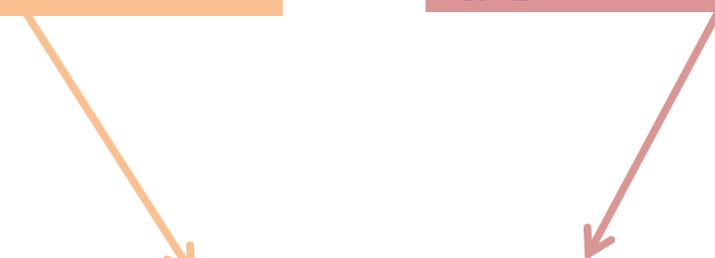
La surface moyenne est considérée comme plan de référence.
Les couches sont numérotées de la face inférieure vers la face supérieure.
Chaque couche k repérée par les cotes algébriques de sa face inférieure (h_{k-1})
et de sa face supérieure (h_k).



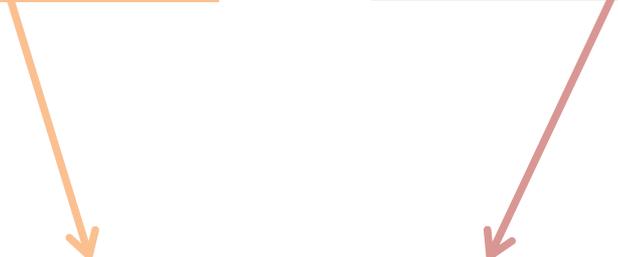
La théorie des stratifiés s'appuie sur les mêmes hypothèses que la théorie générale des plaques.

$$N(x, y) = \sum_{k=1}^{\text{nb plis}} \left([Q]_k \{\varepsilon_0\} \int_{z_{k-1}}^{z_k} dz \right) + \sum_{k=1}^{\text{nb plis}} \left([Q]_k \{K\} \int_{z_{k-1}}^{z_k} z dz \right)$$

$$N(x, y) = \sum_{k=1}^{\text{nb plis}} ([Q]_k (z_k - z_{k-1}) \{\varepsilon_0\}) + \sum_{k=1}^{\text{nb plis}} \frac{1}{2} ([Q]_k (z_k^2 - z_{k-1}^2) \{K\})$$


$$[N] = A \{\varepsilon_0\} + B \{K\}$$

$$M(x, y) = \sum_{k=1}^{\text{nb plis}} \frac{1}{2} ([Q]_k (z_k^2 - z_{k-1}^2)) \{\varepsilon_0\} + \sum_{k=1}^{\text{nb plis}} \frac{1}{3} ([Q]_k (z_k^3 - z_{k-1}^3)) \{K\}$$


$$[M] = B\{\varepsilon_0\} + D\{K\}$$

$$[A] = \sum_{k=1}^{nb \text{ plis}} [Q]_k (z_k - z_{k-1})$$

$$[B] = \frac{1}{2} \left(\sum_{k=1}^{nb \text{ plis}} [Q]_k (z_k^2 - z_{k-1}^2) \right)$$

$$[D] = \frac{1}{3} \left(\sum_{k=1}^{nb \text{ plis}} [Q]_k (z_k^3 - z_{k-1}^3) \right)$$



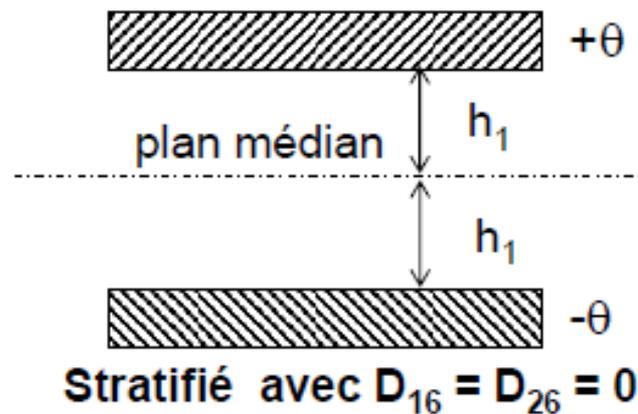
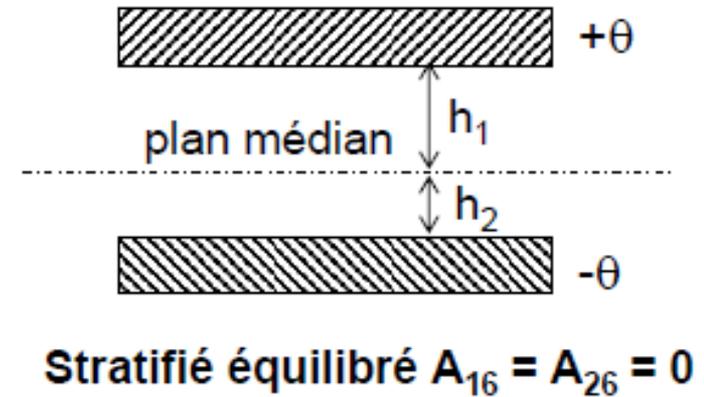
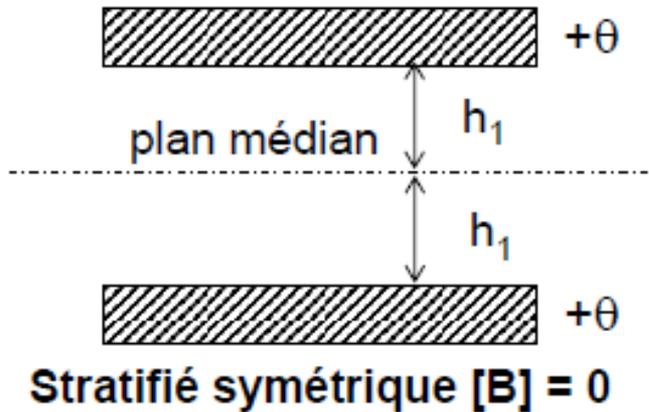
4.2 Assemblages des plis

Relation complète, couplages :

$$\begin{aligned}\{N\} &= A\{\varepsilon_0\} + B\{K\} \\ \{M\} &= B\{\varepsilon_0\} + D\{K\}\end{aligned}$$

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} & A_{xr} \\ A_{yx} & A_{yy} & A_{yr} \\ A_{rx} & A_{ry} & A_{rr} \\ B_{xx} & B_{xy} & B_{xr} \\ B_{yx} & B_{yy} & B_{yr} \\ B_{rx} & B_{ry} & B_{rr} \\ D_{xx} & D_{xy} & D_{xr} \\ D_{yx} & D_{yy} & D_{yr} \\ D_{rx} & D_{ry} & D_{rr} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{Bmatrix}$$

4.3 Règles d'empilement



4.3 Règles d'empilement



+45
-45

129362.13	95762.814	0.	0.	0.	92461.989
95762.814	129363.49	0.	0.	0.	92462.634
0.	0.	104522.61	92461.989	92462.634	0.
0.	0.	92461.989	172482.85	127683.75	0.
0.	0.	92462.634	127683.75	172484.66	0.
92461.989	92462.634	0.	0.	0.	139363.48

-45
+45
+45
-45

258724.27	191525.63	0.	0.	0.	0.
191525.63	258726.99	0.	0.	0.	0.
0.	0.	209045.23	0.	0.	0.
0.	0.	0.	1379862.8	1021470.	- 739695.91
0.	0.	0.	1021470.	1379877.3	- 739701.07
0.	0.	0.	- 739695.91	- 739701.07	1114907.9

-45
+45
0
+45
-45

229864.65	97772.864	0.	0.	0.	0.
97772.864	137403.69	0.	0.	0.	0.
0.	0.	108722.61	0.	0.	0.
0.	0.	0.	342560.72	247554.77	- 138692.98
0.	0.	0.	247554.77	334859.04	- 138693.95
0.	0.	0.	- 138692.98	- 138693.95	270366.75

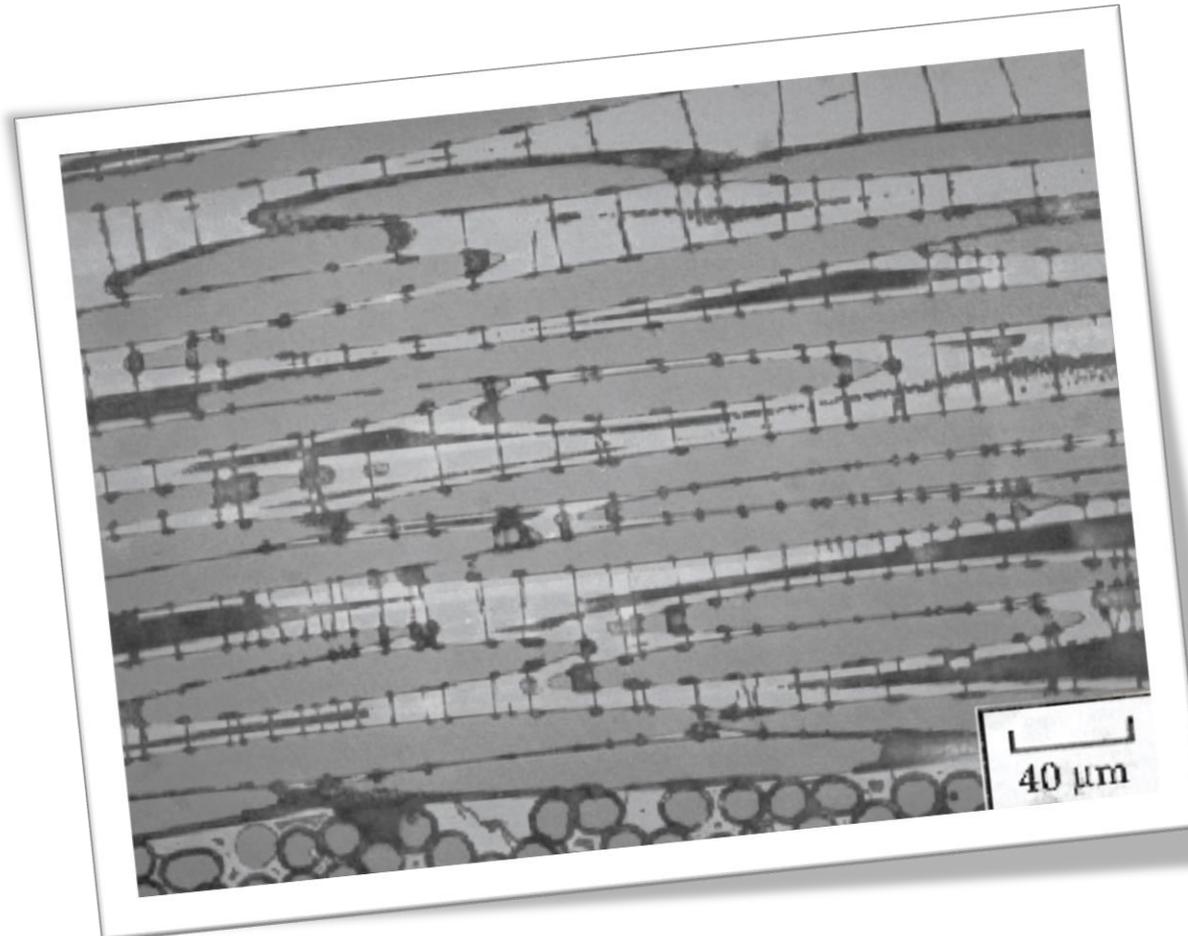
-45
+45
5
+45
-45

228501.	98434.157	7764.3583	0.	0.	0.
98434.157	137444.76	263.61627	0.	0.	0.
7764.3583	263.61627	109383.91	0.	0.	0.
0.	0.	0.	342447.09	247609.88	- 138045.95
0.	0.	0.	247609.88	334862.46	- 138671.98
0.	0.	0.	- 138045.95	- 138671.98	270421.86

-45
+50
0
+45
-45

222498.	97111.544	- 4101.5601	7366.6512	661.32072	4101.5601
97111.544	146092.99	3399.1722	661.32072	- 8689.2927	- 3399.1722
- 4101.5601	3399.1722	108061.29	4101.5601	- 3399.1722	661.32072
7366.6512	661.32072	4101.5601	334580.19	246838.34	- 143136.34
661.32072	- 8689.2927	- 3399.1722	246838.34	344272.44	- 135011.51
4101.5601	- 3399.1722	661.32072	- 143136.34	- 135011.51	269650.32

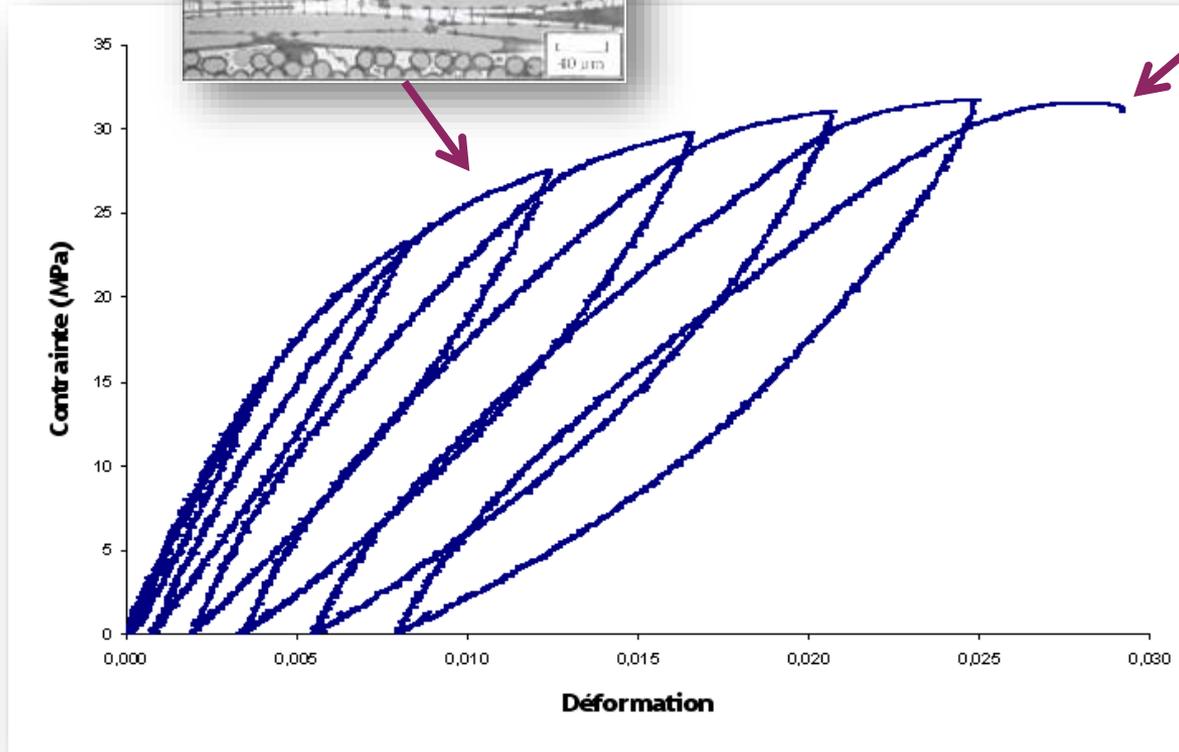
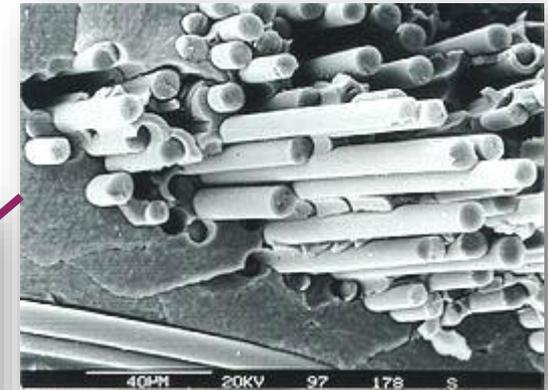
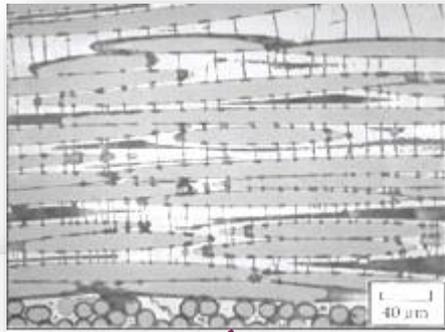
5 Endommagement

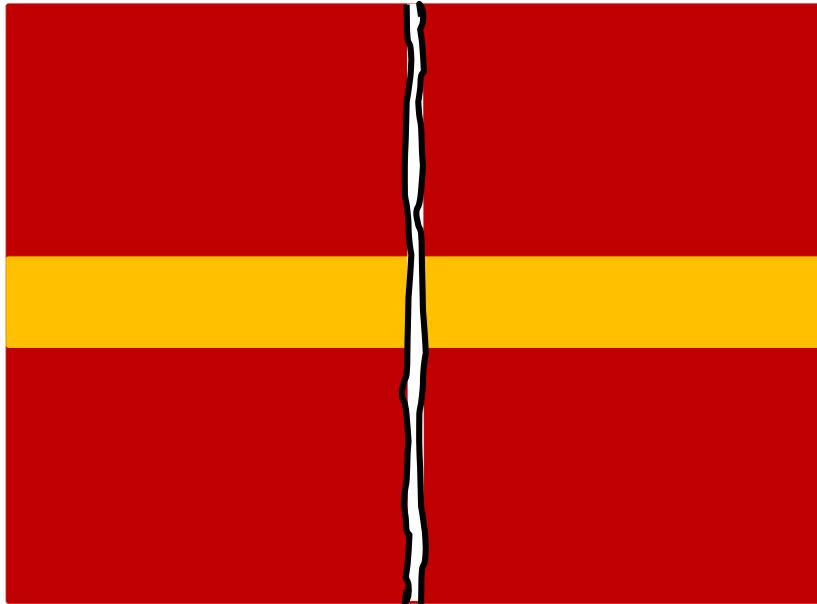


Les matériaux composites peuvent dissiper l'énergie non-élastique de 4 façons principales :

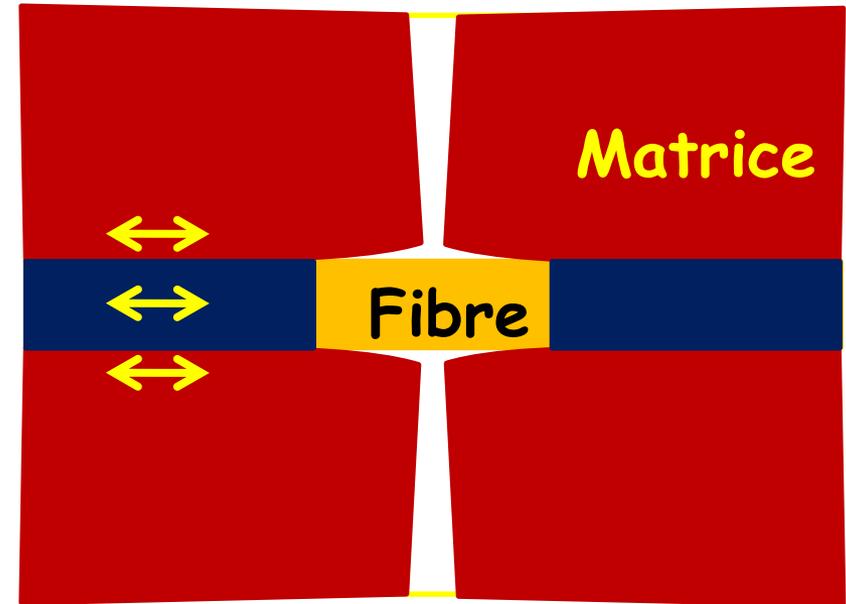
1. Multifissuration
2. Délaminage
3. Décohésion
4. Rupture de fibres

Non linéarité = endommagement = (multi)fissuration

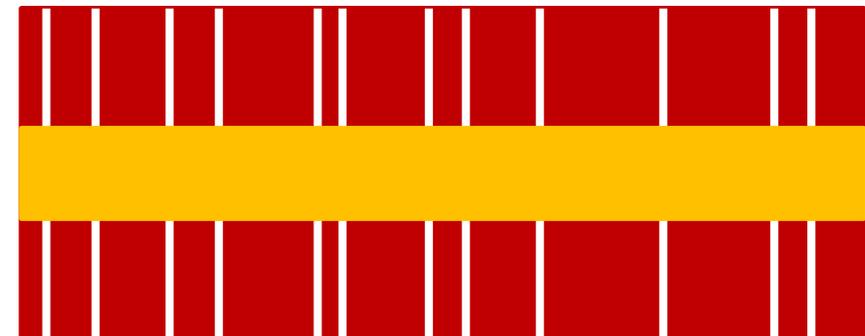
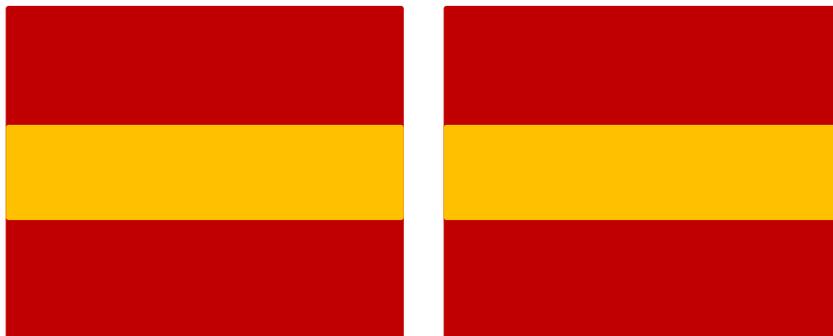




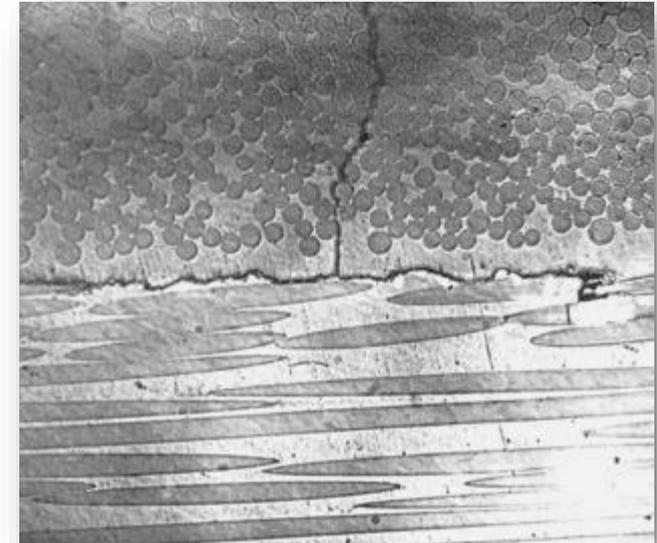
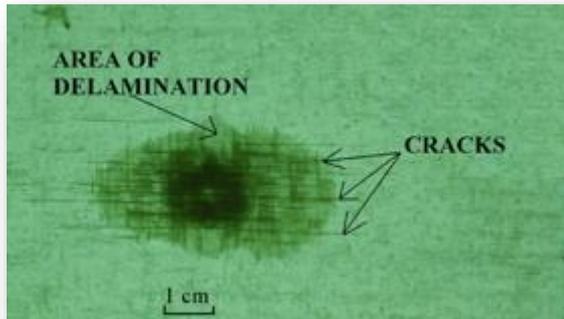
Liaison forte



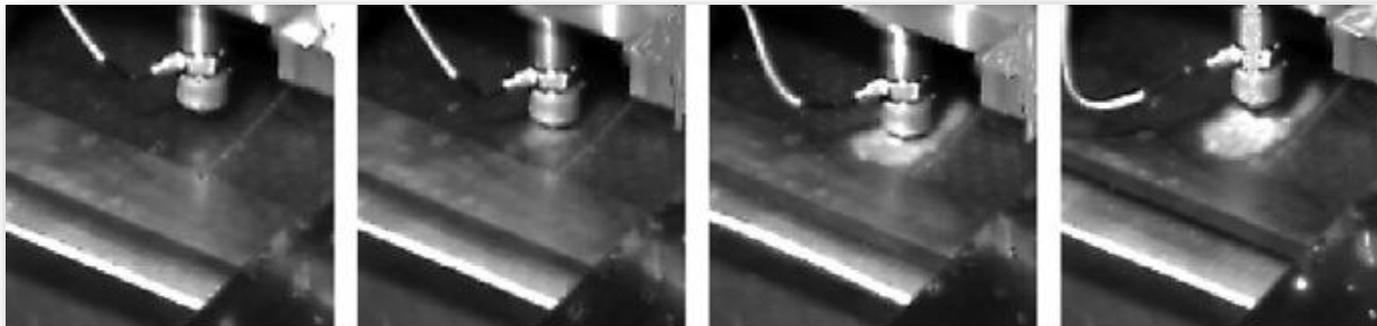
Liaison bien dosée



Séparation de deux couches adjacentes
Deux directions de fibres différentes et θ important

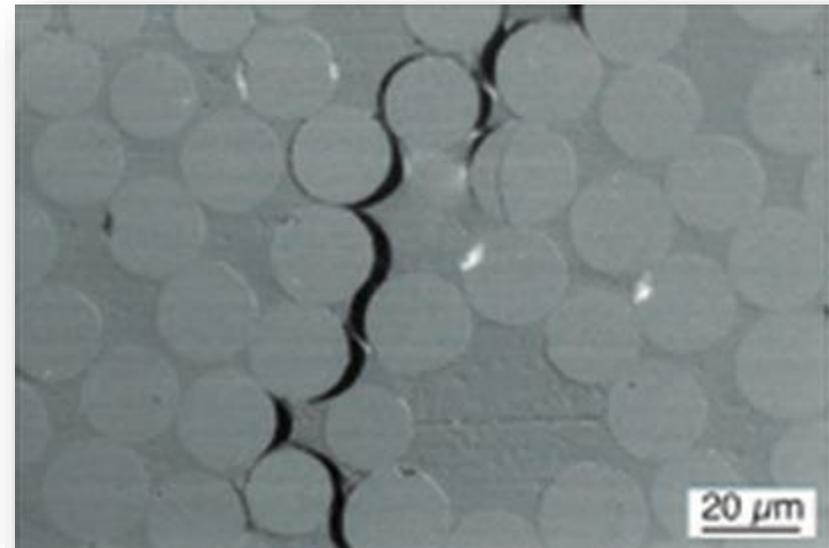
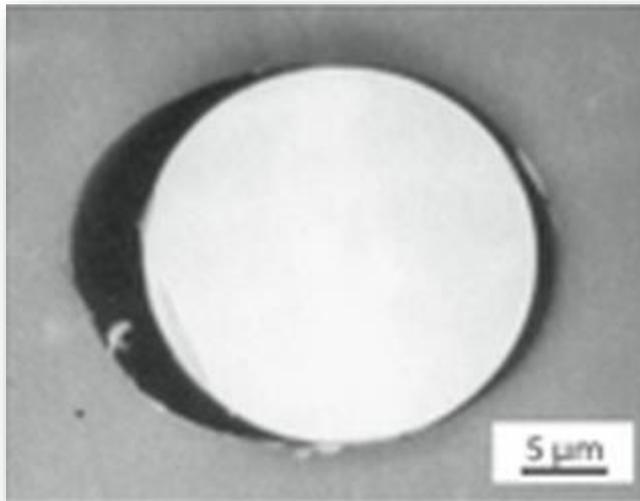


Observation par vidéo rapide :

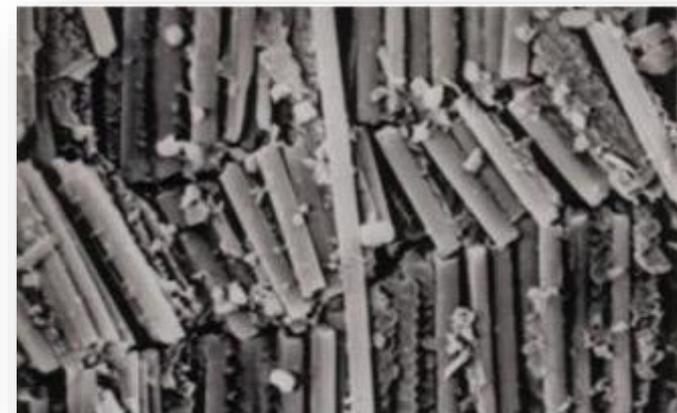
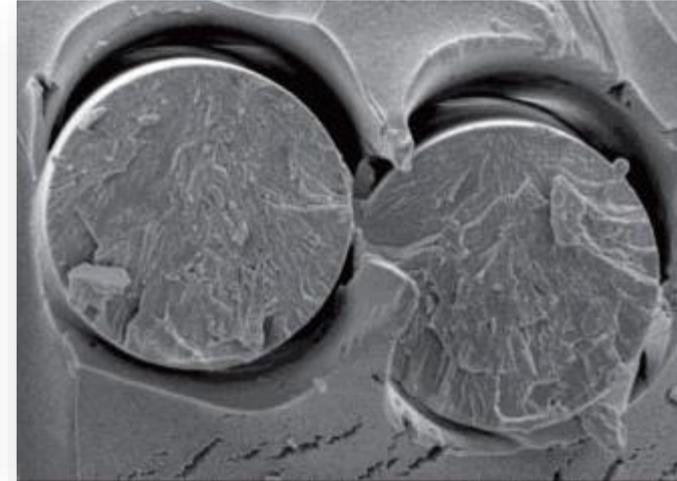
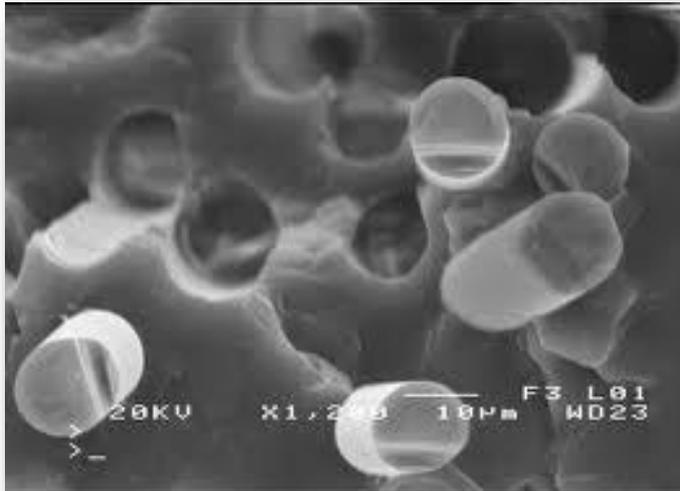


La fibre se décolle de la matrice :

1. Action de fissures
2. Différence de coefficient de dilatation thermique
3. Mauvaise adhésion fibre/matrice



Ce phénomène survient généralement à la fin du comportement



Rupture en compression (kink-band) →