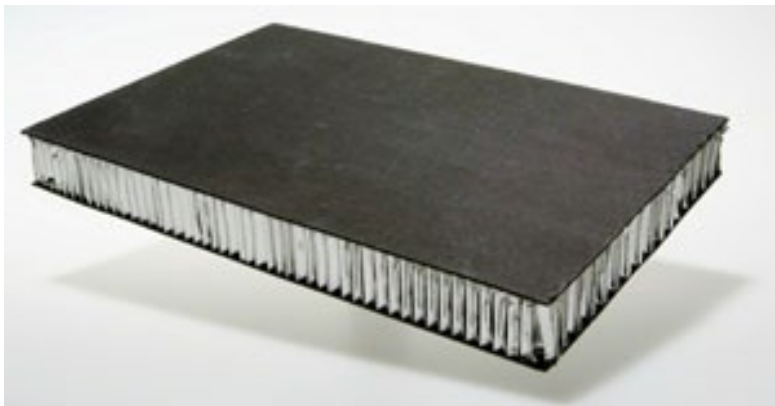


# Composite Technology

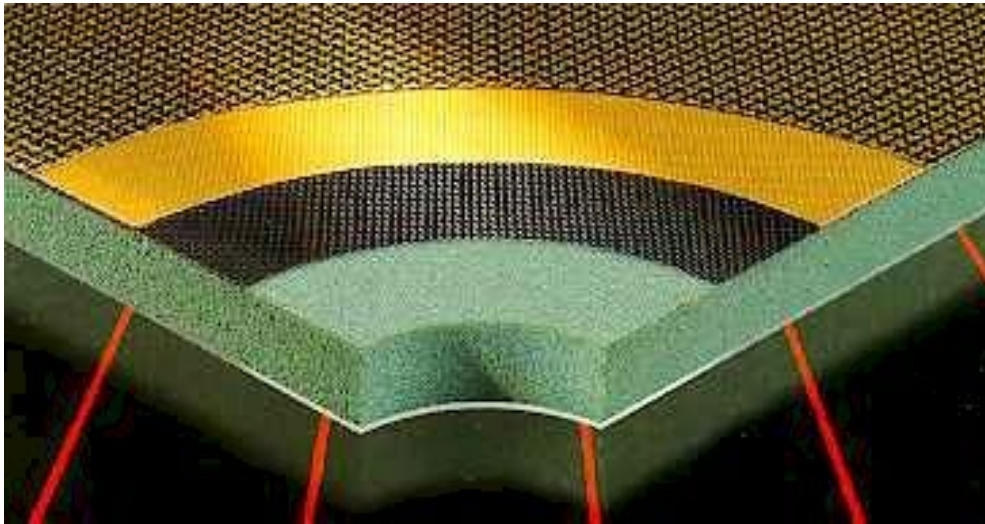
## Sandwich structures

pierre-etienne.bourban@epfl.ch

Institut des matériaux (IMX)  
Ecole Polytechnique Fédérale de Lausanne (EPFL),  
CH-1015 Lausanne




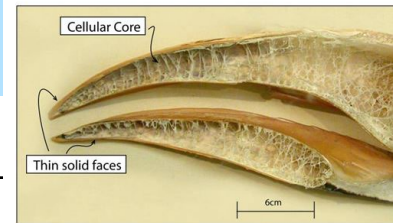
# Sandwich



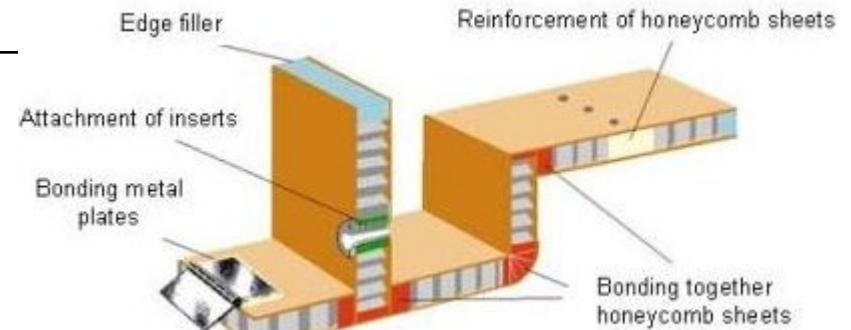
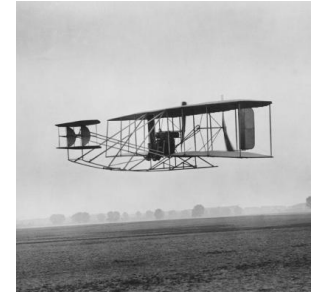
- **Introduction**
- **Materials**
- **Sandwich effect**
- **Processing**

# History

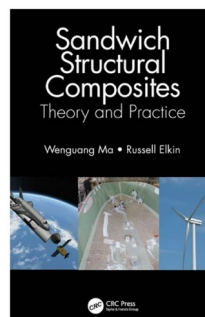
1820	Duleau, Fairbairn: first concept 	
1920	Fuselage	
'30	Development of structural adhesives	
WW2	MOSQUITO airplane (sandwich with Balsa core)	
1950	Honeycomb Aerospace industry	$\tau/\rho$ , $E/\rho$ higher !!!! Bonding and cost !!!!
1960	Foam cores PVC, PU	For lower cost applications
1970	FEM	
	Processing methods    Quality control Joining    Cellular thermoplastic cores....	



<http://www.virginia.edu/ms/research/wadley/cellular-materials.html>

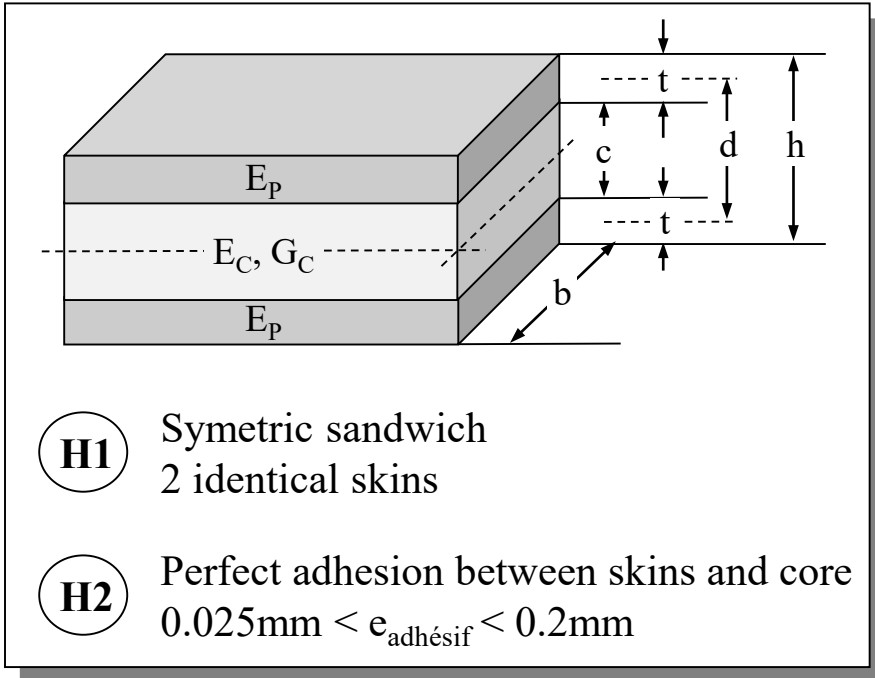


D. Zenkert: *The handbook of sandwich construction*, EMAS 1997  
ALCAN, AIREX, SIMS, EUROCOMPOSITES



<http://www.adhesives.org/adhesives-sealants/market-overview-applications/transportation>

# Sandwich effect



$$D = \text{Bending stiffness} = \sum E_i I_i \quad \text{with: } I_C = \frac{b c^3}{12}$$

$$I_P = \frac{b t^3}{12} + \frac{b t d^2}{4}$$

$$D = \underbrace{2 E_P I_P}_{D_p} + \underbrace{E_C I_C}_{D_c} = E_P \frac{b t^3}{6} + E_P \frac{b t d^2}{2} + E_C \frac{b c^3}{12}$$




$t \ll d \rightarrow \approx 0$        $E_C \text{ small} \rightarrow \approx 0$

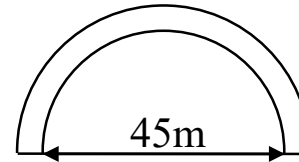
$$D \approx D' = E_P \frac{b t d^2}{2}$$

usually:  $10 < \frac{c}{t} < 50$  et  $50 < \frac{E_P}{E_C} < 1000$

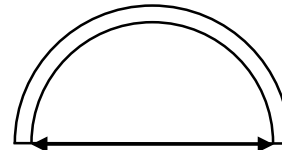
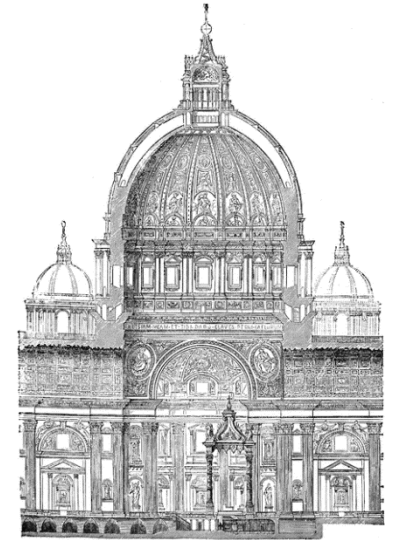
If no adhesion between skins and core :  $D \sim 0$

# Sandwich effect

	weight	D	$\sigma$ bending
 t	1	1	1
2t  t/2	~1	~ 12	~ 6
4t  t/2	~ 1	~ 48	~ 12



Roma,  
Dome of St-Peter's  
Stone:  $\text{kg/m}^2$



Tianjin Stadium  
Sandwich  
(Al skins and foam core):  
 $\text{kg/m}^2$

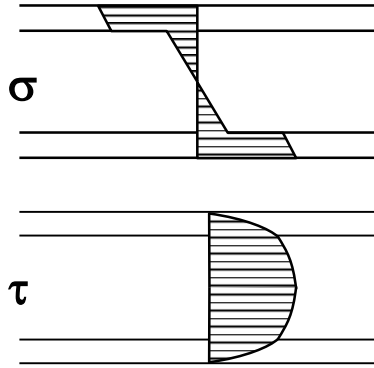


<http://www.archiexpo.fr/prod/euramax-coated-products/product-63750-1295957.html>

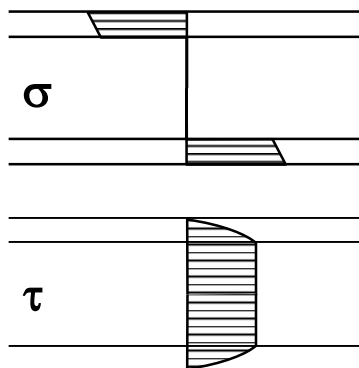
[https://etc.usf.edu/clipart/73700/73702/73702\\_st\\_peters.htm](https://etc.usf.edu/clipart/73700/73702/73702_st_peters.htm)

# Stress distribution ( $\sigma$ et $\tau$ )

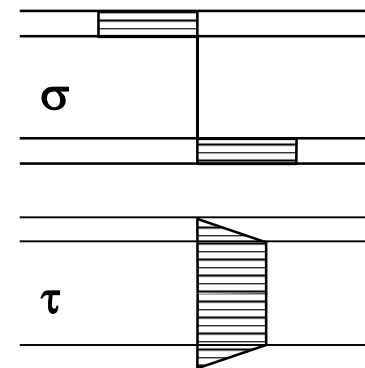
Without approximation



$E_c \ll E_f$



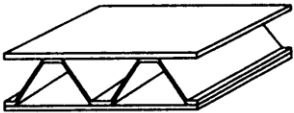
$E_c \ll E_f$  et  $t_c \gg t_f$



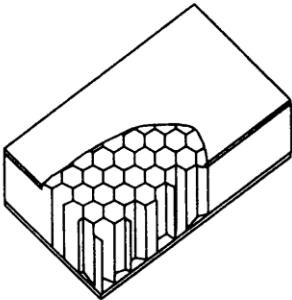
$\sigma_p(z)$	$\frac{M_x z E_f}{D}$	$\frac{M_x z E_f}{D_p}$	$\frac{M_x}{t d}$	$\frac{c}{2} <  z  < \frac{c}{2} + t$
$\sigma_c(z)$	$\frac{M_x z E_c}{D}$	0	0	$ z  < \frac{c}{2}$
$\tau_p(z)$	$\frac{T_x}{D} \frac{E_p}{z} \left( \frac{c^2}{4} + c t + t^2 - z^2 \right)$	$\frac{T_x}{D} \frac{E_p}{z} \left( \frac{c^2}{4} + c t + t^2 - z^2 \right)$	0	$\frac{c}{2} \leq  z  \leq \frac{c}{2} + t$
$\tau_c(z)$	$\frac{T_x}{D} \left[ \frac{E_p t d}{2} + \frac{E_c}{2} \left( \frac{c^2}{4} - z^2 \right) \right]$	$\frac{T_x E_p t d}{2 D_p}$	$\frac{T_x}{d}$	$ z  \leq \frac{c}{2}$

Stresses  $\sigma$  are maximum into the skins  
 $\tau$  is max into the core

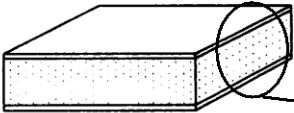
# Materials



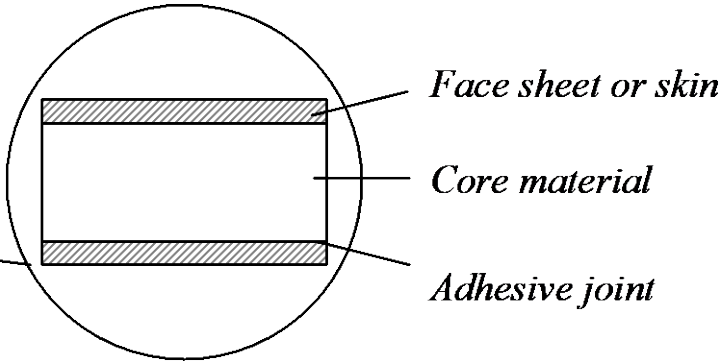
*Corrugated*



*Honeycomb*

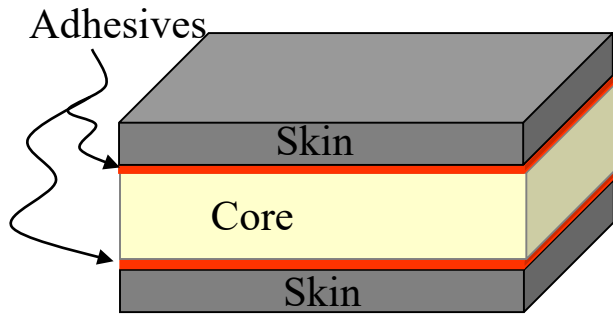


*Balsa or cellular foam*



*Typical sandwich cross-section*

# Materials

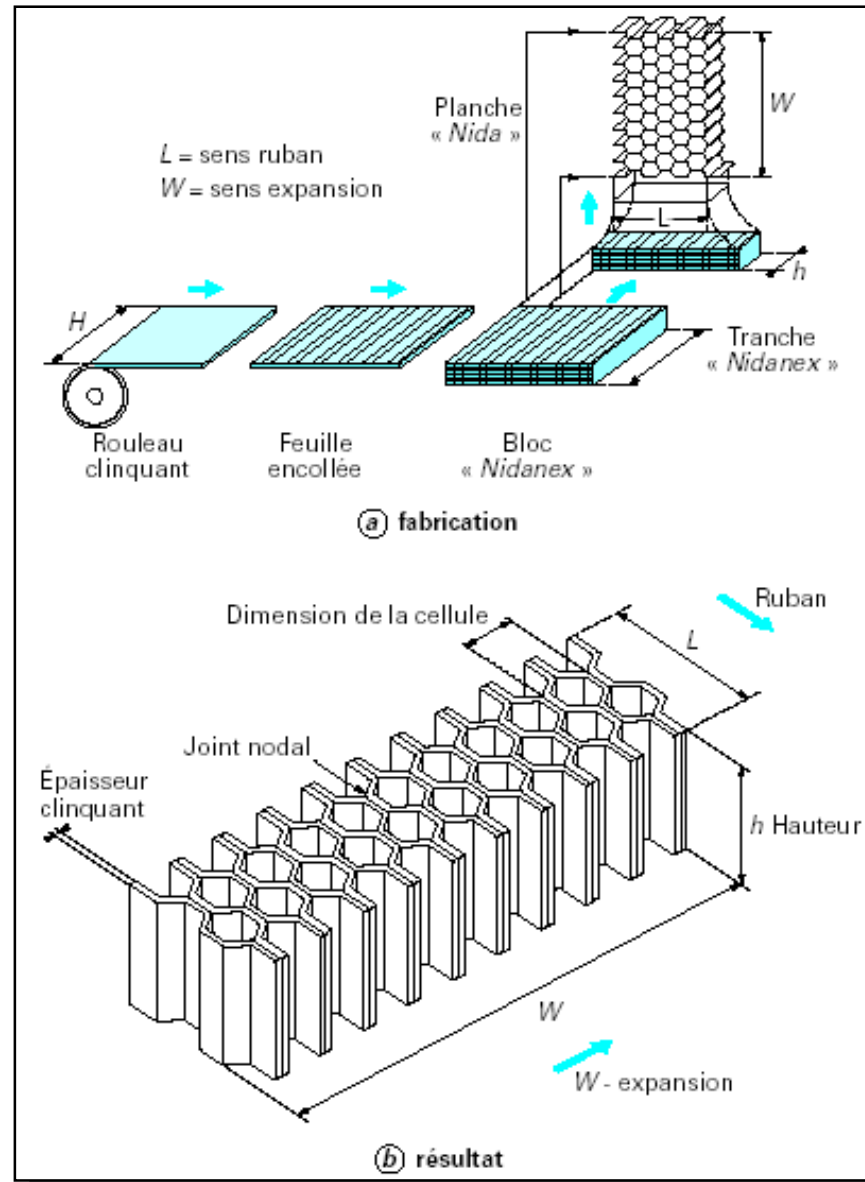
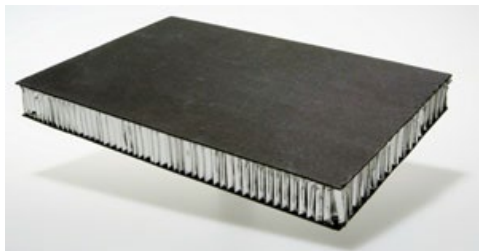


Skins			
	$\rho$ [kg/m <sup>3</sup> ]	E [GPa]	$\sigma$ [MPa]
<b>Steel</b>	2700-8000	70-210	200-1000
<b>Wood</b>	~500	~12	20-40
<b>UD composites</b>	~1600	40-200	1000-1200
<b>Bi-directional composites</b>	~1600	15-100	200-800
<b>Mats</b>	~1700	~10	80-150

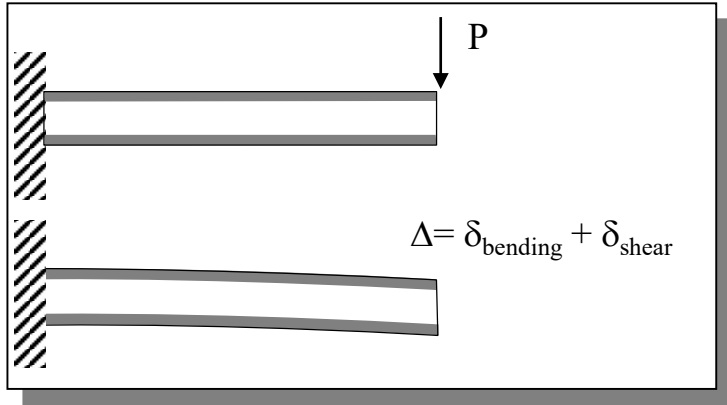
Cores		
	$\rho$ [kg/m <sup>3</sup> ]	$\tau$ [MPa]
<b>Honeycombs (Al/ Nomex/TP)</b>	20-100	0.2-2
<b>Balsa</b>	150	2
<b>Foam</b>	15-80	0.2-3

+ Adhesives

# Honeycombs



# Sandwich beams



$\textcircled{\text{H}}$   $t \ll c ; E_c \ll E_p$

Bending stiffness:  $D = \frac{E_f t d^2}{2}$   
 Shear stiffness:  $S = \frac{G_c d^2}{c}$

Bending deformation:  $\delta_{\text{bending}} = \frac{P L^3}{3D} = \frac{2 P L^3}{3 E_p t d^2}$   
 Shear deformation:  $\delta_{\text{shear}} = \int_0^L \frac{T_x}{S} dx = \frac{P L}{S}$

$\Delta = \frac{2 P L^3}{3 E_p t d^2} + \frac{P L c}{G_c d^2}$

## Sandwich:

$t = 1 \text{ mm}$

$c = 30 \text{ mm}$

$L = 500 \text{ mm}$

$G_c = 30 \text{ MPa}$  (80kg/m<sup>3</sup> PVC foam)

$E_f = 200\,000 \text{ MPa}$  (steel)

$\delta_{\text{bending}} = 0.43 P \text{ mm/N}$

$\delta_{\text{shear}} = 0.52 P \text{ mm/N}$

$\left. \begin{array}{l} \delta_{\text{bending}} = 0.43 P \text{ mm/N} \\ \delta_{\text{shear}} = 0.52 P \text{ mm/N} \end{array} \right\} \frac{\delta_{\text{bending}}}{\delta_{\text{shear}}} = 0.83$

## Steel beam:

$h = 30 \text{ mm}$

$L = 500 \text{ mm}$

$E_f = 200\,000 \text{ MPa}$  (steel)

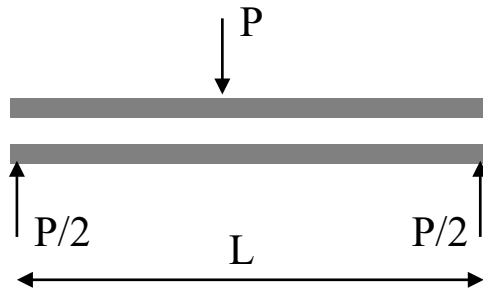
$\delta_{\text{bending}} = \frac{P L^3}{3D} = \frac{4 P L^3}{E h^3} = 0.0926 P \text{ mm/N}$

$\delta_{\text{shear}} = \frac{P L}{S} = 1.2 \frac{P L}{G h} = 0.0003 P \text{ mm/N}$

$\left. \begin{array}{l} \delta_{\text{bending}} = 0.0926 P \text{ mm/N} \\ \delta_{\text{shear}} = 0.0003 P \text{ mm/N} \end{array} \right\} \frac{\delta_{\text{bending}}}{\delta_{\text{shear}}} = 310$

# Sandwich testing

## 3 points bending



$$M_{\max} = \frac{PL}{4} \quad \text{et} \quad T_{\max} = \frac{P}{2}$$

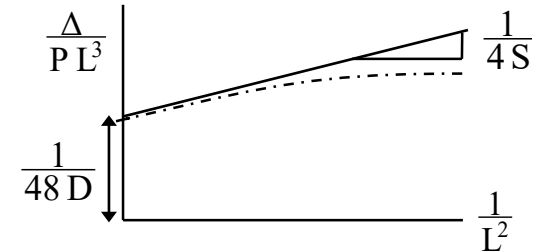
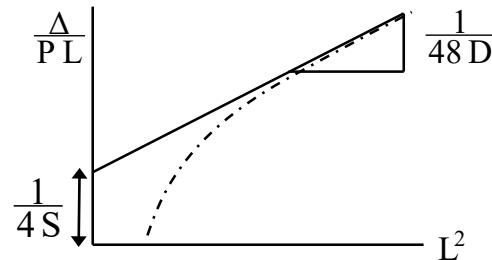


allow to calculate  $\sigma$  max in the skins and  $\tau$  max in the core

$$\Delta = \delta_{\text{flexion}} + \delta_{\text{cisaillement}} = \frac{PL^3}{48D} + \frac{PL}{4S}$$

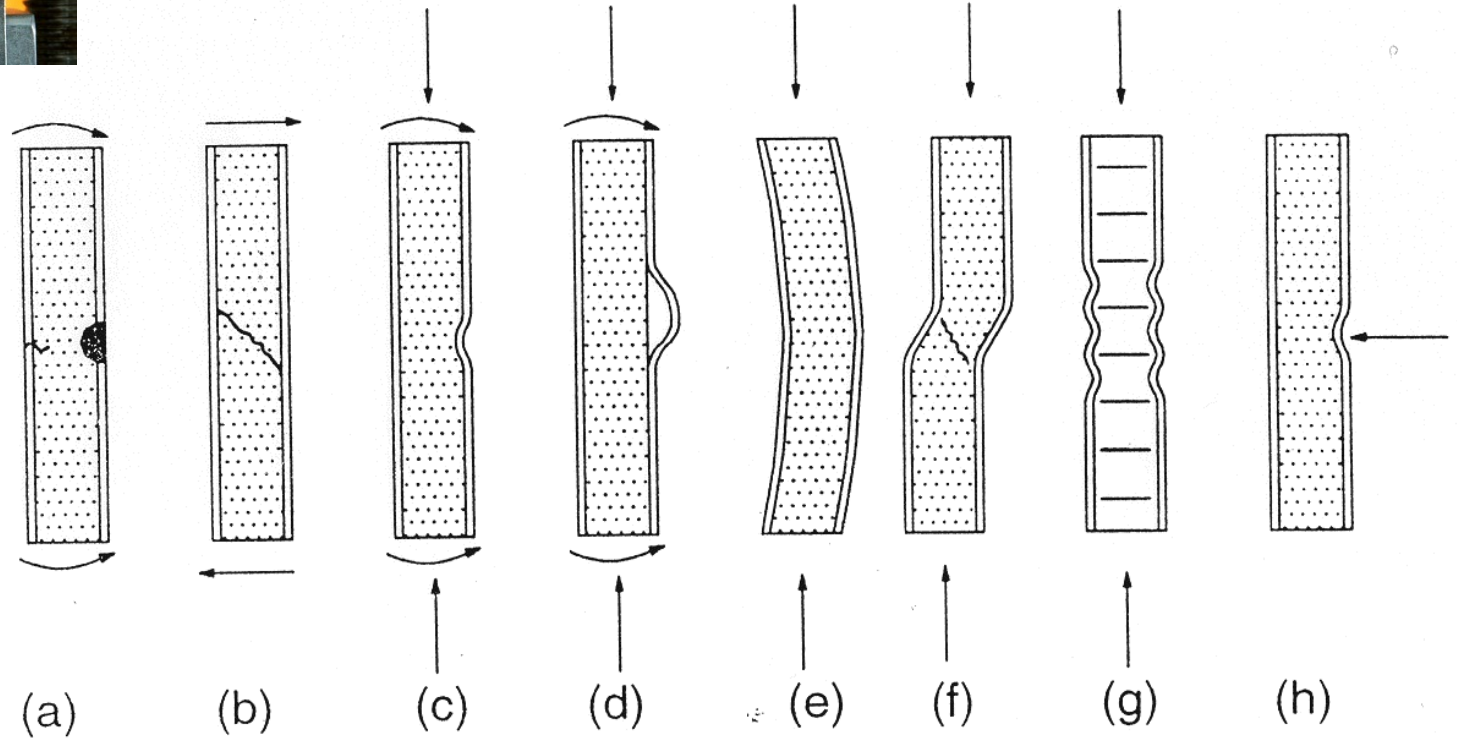
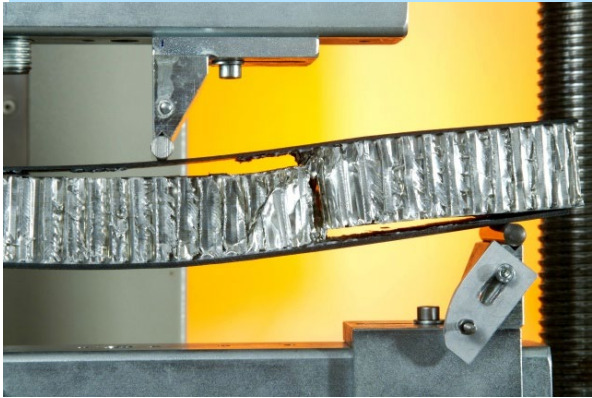
$$\frac{\Delta}{PL} = \frac{L^2}{48D} + \frac{1}{4S}$$

$$\frac{\Delta}{PL^3} = \frac{1}{48D} + \frac{1}{4S} \frac{1}{L^2}$$



=> Measurements of D et S

# Damage in sandwich



- (a) Face yielding/fracture
- (b) Core shear failure
- (c, d) Face wrinkling
- (e) General buckling

Debonding  
Impact damage

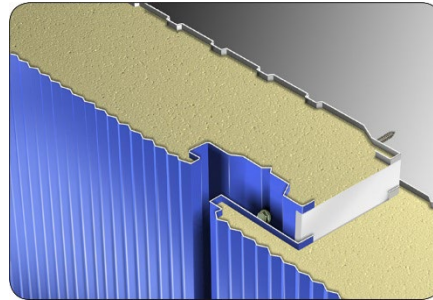
- (f) Shear crimping
- (g) Face dimpling
- (h) Local indentation

# Some applications

Sport (skis, boards, F1...)  
 Transportation  
 Infrastructures



<http://sdshuangli.en.alibaba.com>



<http://www.giesselogistica.eu/en/sandwichpanels/>



	$t_p$ (mm)	$t_c$ (mm)	$M_{max}$ (Nm) verre	$M_{max}$ (Nm) carbone
Airplanes	0.5	10	300	1000
Racing cars				
Sailing boats	1.5	25	5000	19000
Large boats	5	60	99000	360000

[www.hexcelcomposites.com](http://www.hexcelcomposites.com)  
[www.eurocomposites.com](http://www.eurocomposites.com)

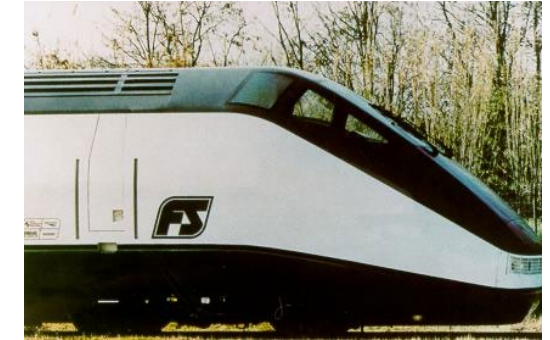
# Processing methods

## 2 main routes

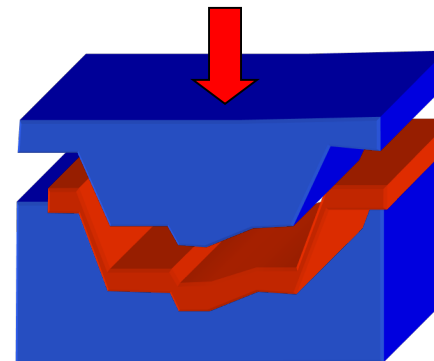
- bonding and reticulation of the two skins at same time
- processing of the skins and then bonding

## Main methods

- wet lay-up
- prepregs
- liquid moulding/ RTM, VARTM, SRIM...
- continuous lamination
- others: compression, pultrusion, filament winding



Front-end cabin,  
ETR500 high speed Italian train.  
Vacuum-bag, FRP, PEI foam

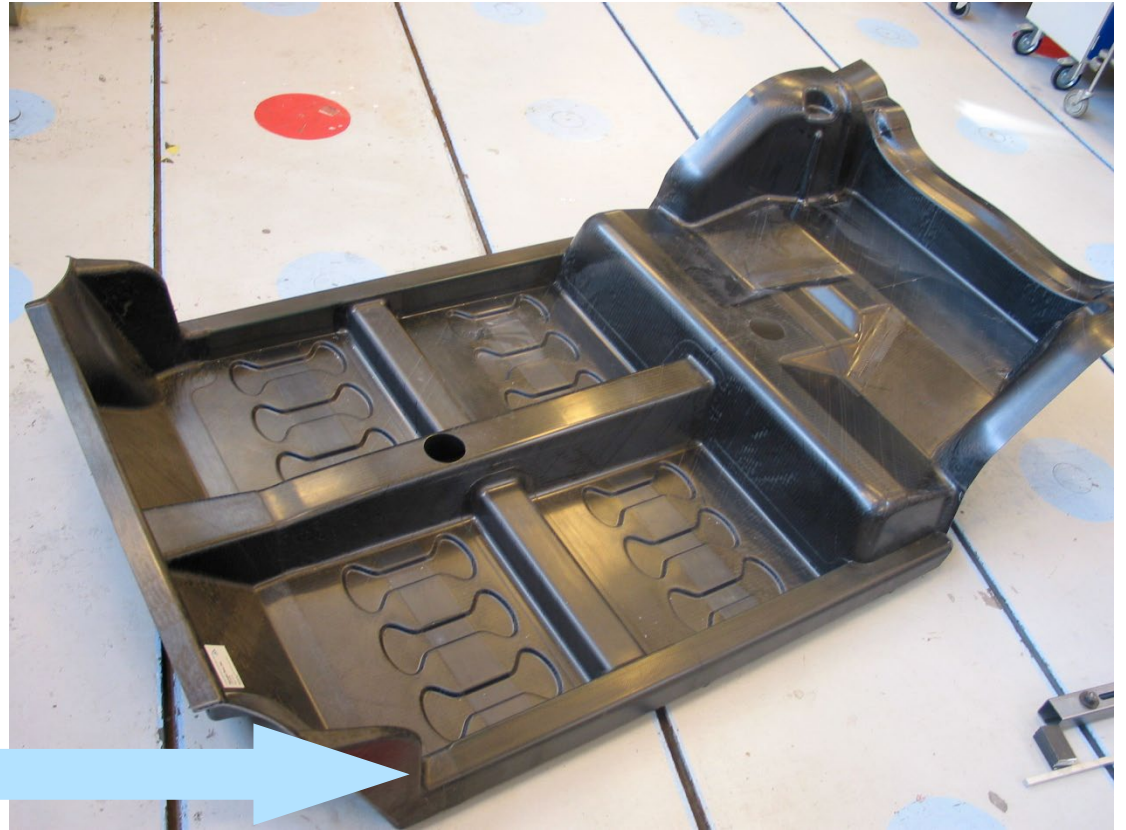
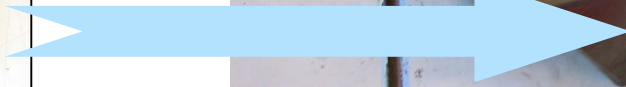
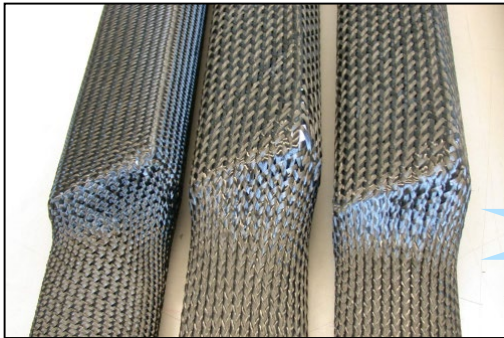


## Some issues

- bonding quality
- release of foaming gaz
- spiking of skins...

Ref: K.F.Karlsson and B.T. Astrom, « Manufacturing and applications of structural sandwich components », *Composites Part A*, 28 A (1997), pp.97-111

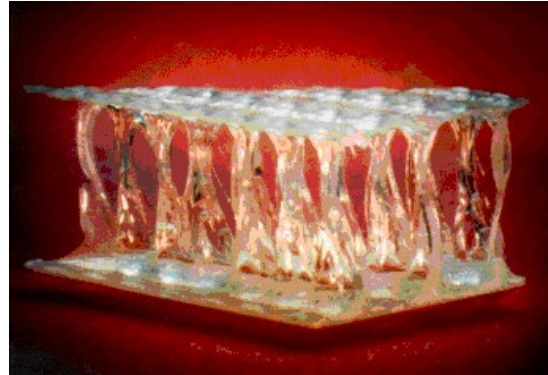
# RTM



VW Lupo, prototype platform

# Evolutions... cellular materials

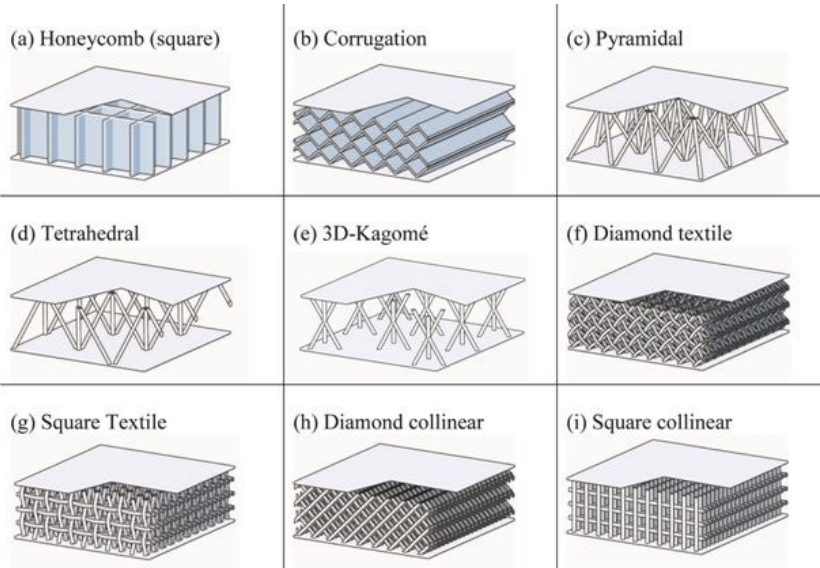
3D textiles structures for sandwich ( cf Textile composites)



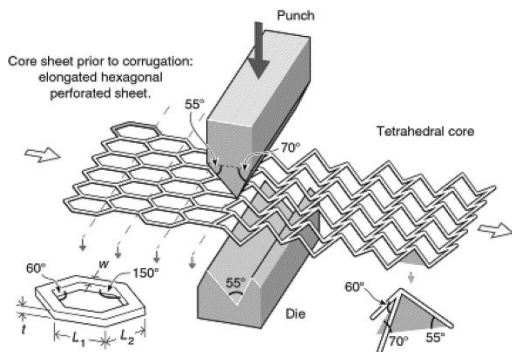
Cellular composites ( cf Biocomposites)



# Evolutions... cellular materials

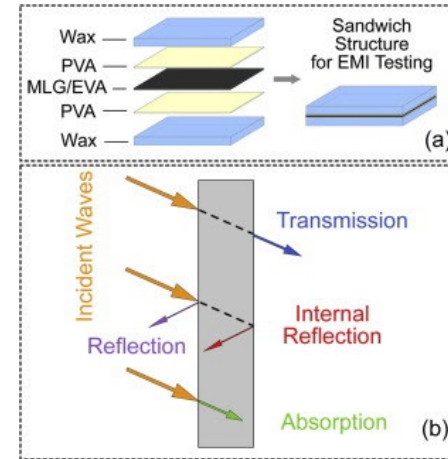


<http://www.virginia.edu/ms/research/wadley/cellular-materials.html>

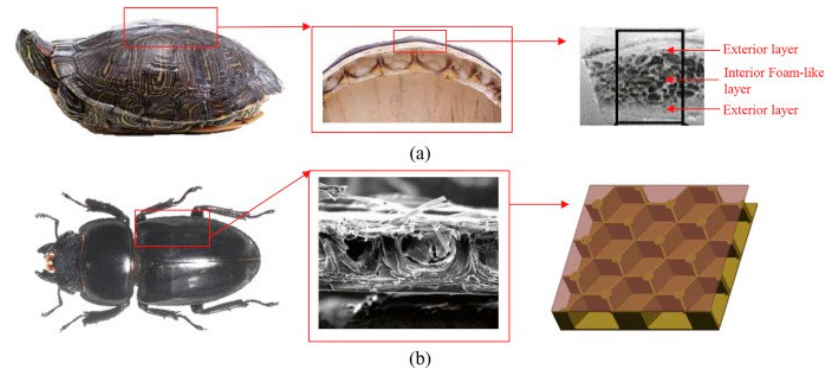


**Fabrication and structural performance of periodic cellular metal sandwich structures**  
Composites Science and Technology 63 (2003) 2331–2343

*pierre-etienne.bourban@epfl.ch*



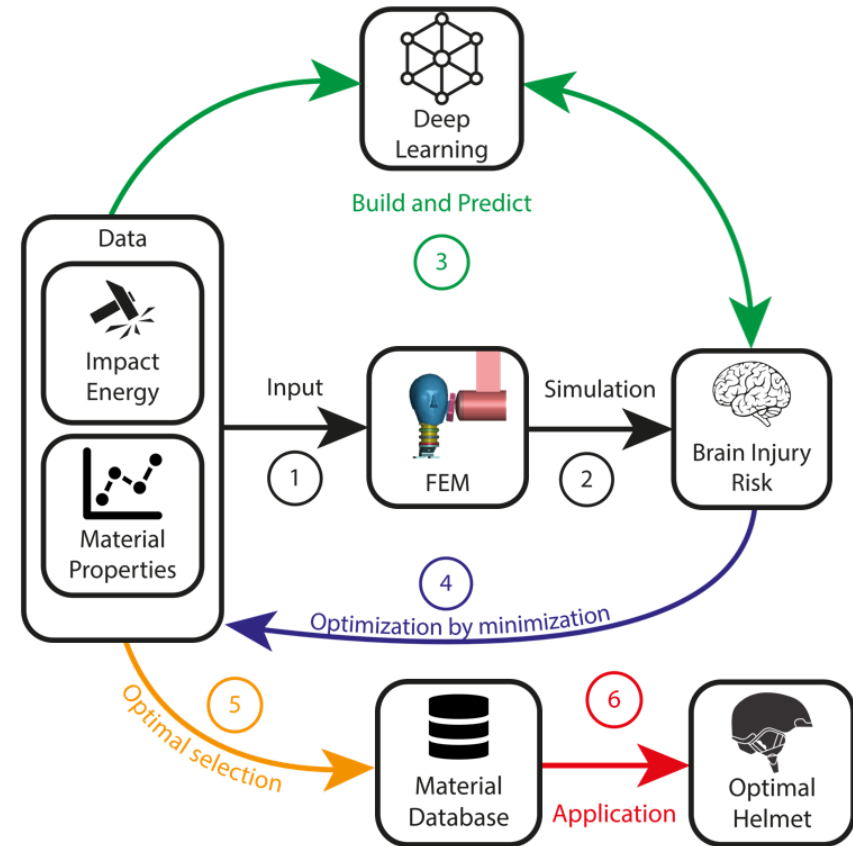
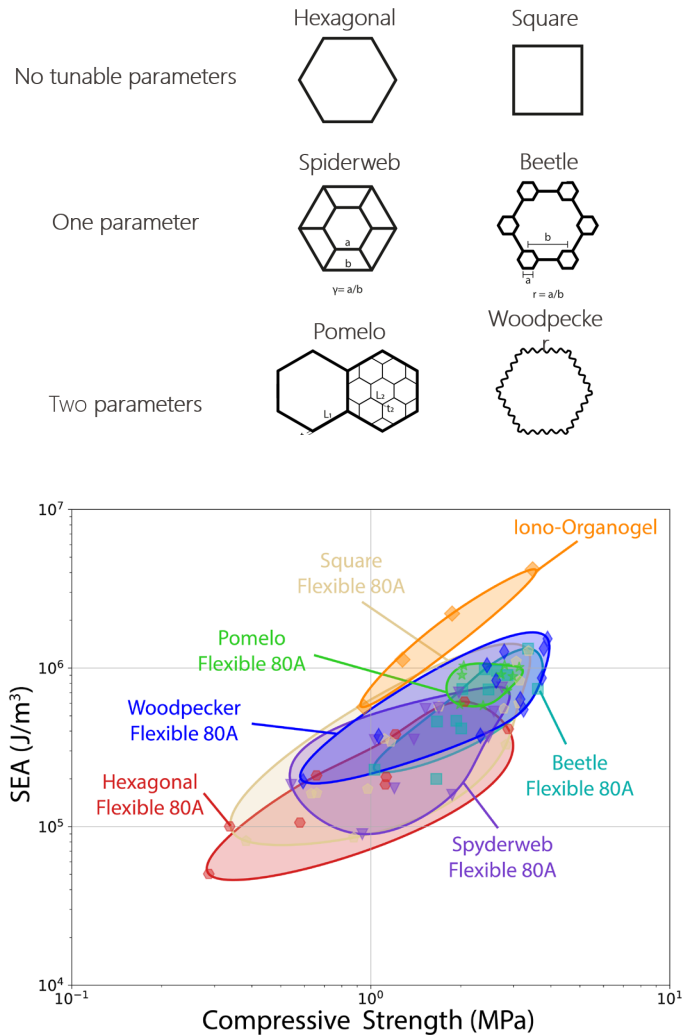
**Flexible graphene/polymer composite films in sandwich structures for effective electromagnetic interference shielding**  
Carbon, Volume 66, January 2014, Pages 67-76



**Dynamic crash responses of bio-inspired aluminum honeycomb sandwich structures with CFRP panels**

Composites Part B: Engineering, Volume 121, 15 July 2017, Pages 122-133

# Lattice structures optimization and combinations for Specific Energy Absorption



Inverse material design to tailor helmet protection against brain injury, Vincent Varanges, EPFL-Thèse 11345, 2025