

The EPFL logo is rendered in a bold, red, sans-serif font. It is positioned at the top center of the slide, partially enclosed by a large, stylized graphic element consisting of two overlapping, curved bands in light blue and light green.

Prof. Anastasios P. Vassilopoulos

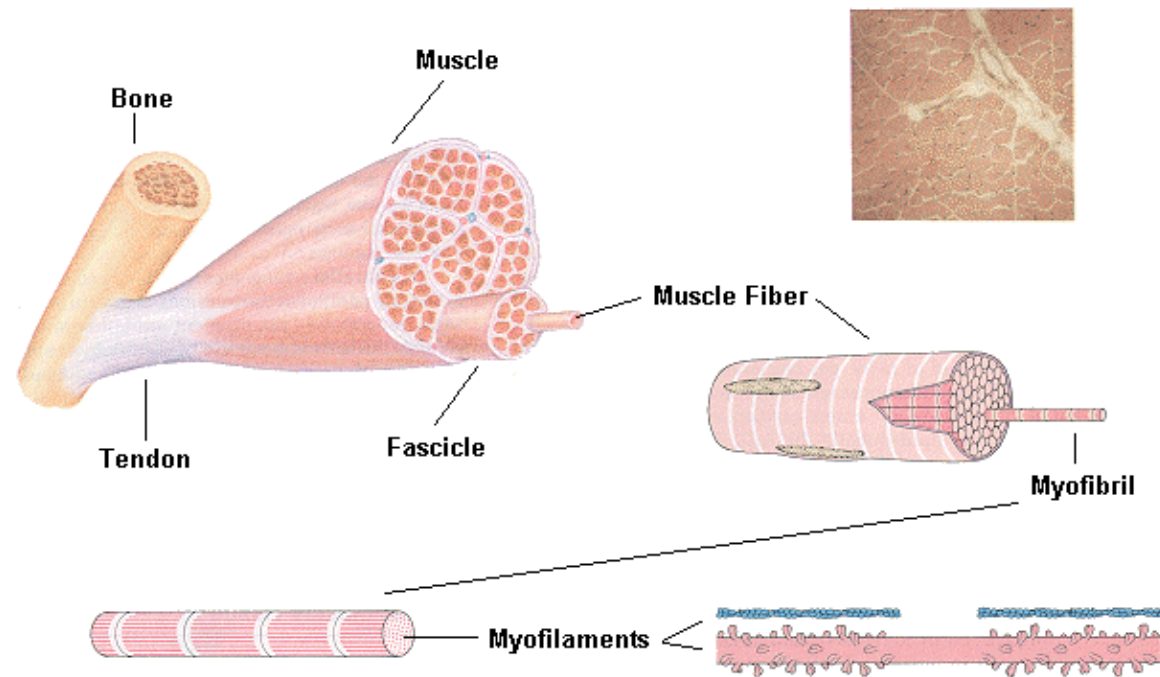
Advanced composites in engineering structures

Lecture #2

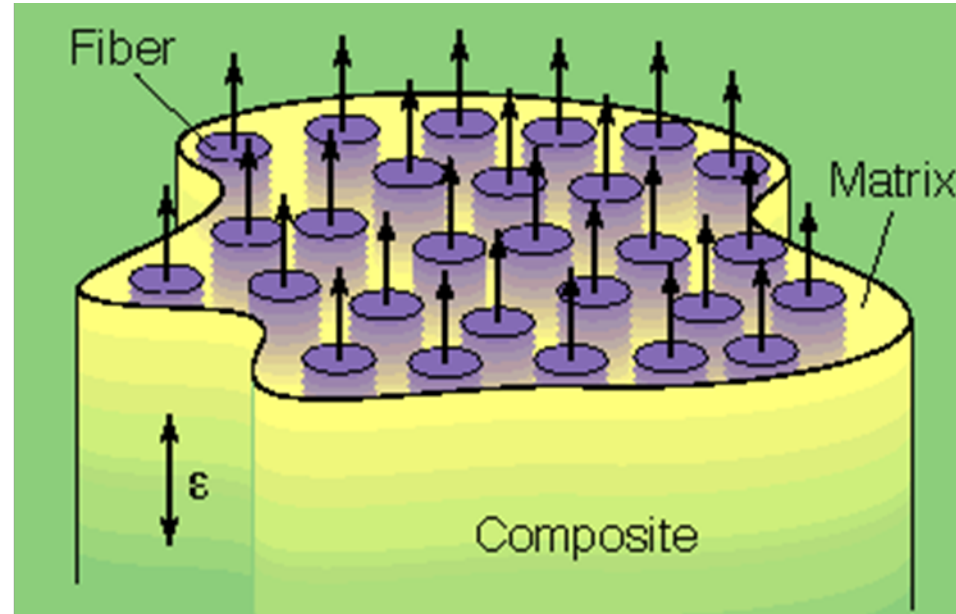
The GRoMeC logo features the text "GRoMeC" in a blue, sans-serif font. The letter "o" is replaced by a circular icon containing vertical lines. Below this, the text "Composite Mechanics Group" is written in a smaller, black, sans-serif font. The logo is located in the bottom right corner of the slide, partially enclosed by the same stylized blue and green graphic element seen at the top.

Composite materials (Concept)

- An old concept-Natural composites
 - All natural materials (structures) that must bear load are composites (muscles, wood, bones...)



Advanced structural composites



Composites consist of one or more discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and is called the reinforcement or reinforcing material, whereas the continuous phase is termed the matrix.

Composite in structural engineering

- A new industry-engineering composites



Composite in structural engineering

- A new industry-engineering composites



Composite in structural engineering



FRP bridge

- The Nelson Mandela Bridge



...the largest movable road bridge in FRP in the world.

<https://www.mct.nl/en/projects/nelson-mandela-bridge-alkmaar/>
<https://www.nationalestaalprijs.nl/project/verkeersbrug-nelson-mandelabrug>
<https://bruggenstichting.nl/tijdschrift/ouder/61-bruggen/bruggen-2017/664-vezelversterkt-kunststof-komt-over-de-brug>

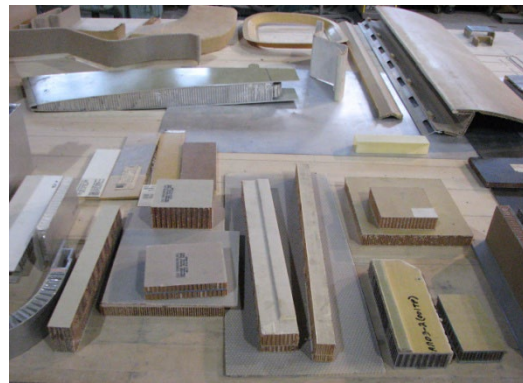
Client	Provincie Noord-Holland / Gemeente Alkmaar
City	Alkmaar
Country	Netherlands
Scope	Total length 67 meters, lifting deck 22,5 x 14,5 m
Period	2013 - 2016
Expertise	Architecture, Project Management, Structural Design
Team	Joris Smits, Sven Spierings, Liesbeth Tromp, André Fase



Lamborghini Aventador monocoque chassis

Source:

<http://www.lamborghini.com/en/models/aventador-lp-700-4/innovation-technology/chassis/>



Royal Navy mine counter measures vessel - HMS Wilton: 450 tons - 46.3 m long - monolithic GRP

HMS Wilton was a world leader at the time of her construction in 1973. At 450 tons, she was then the world's largest reinforced plastic ship. Unofficially known as HMS Tupperware, HMS Indestructible, or just 'the plastic duck', HMS Wilton was built to the tried and tested Coniston-class mine hunter design (more usually called the Ton class minesweeper).

Source: <http://www.tech.plym.ac.uk/sme/composites/marine.htm>





Modern blades

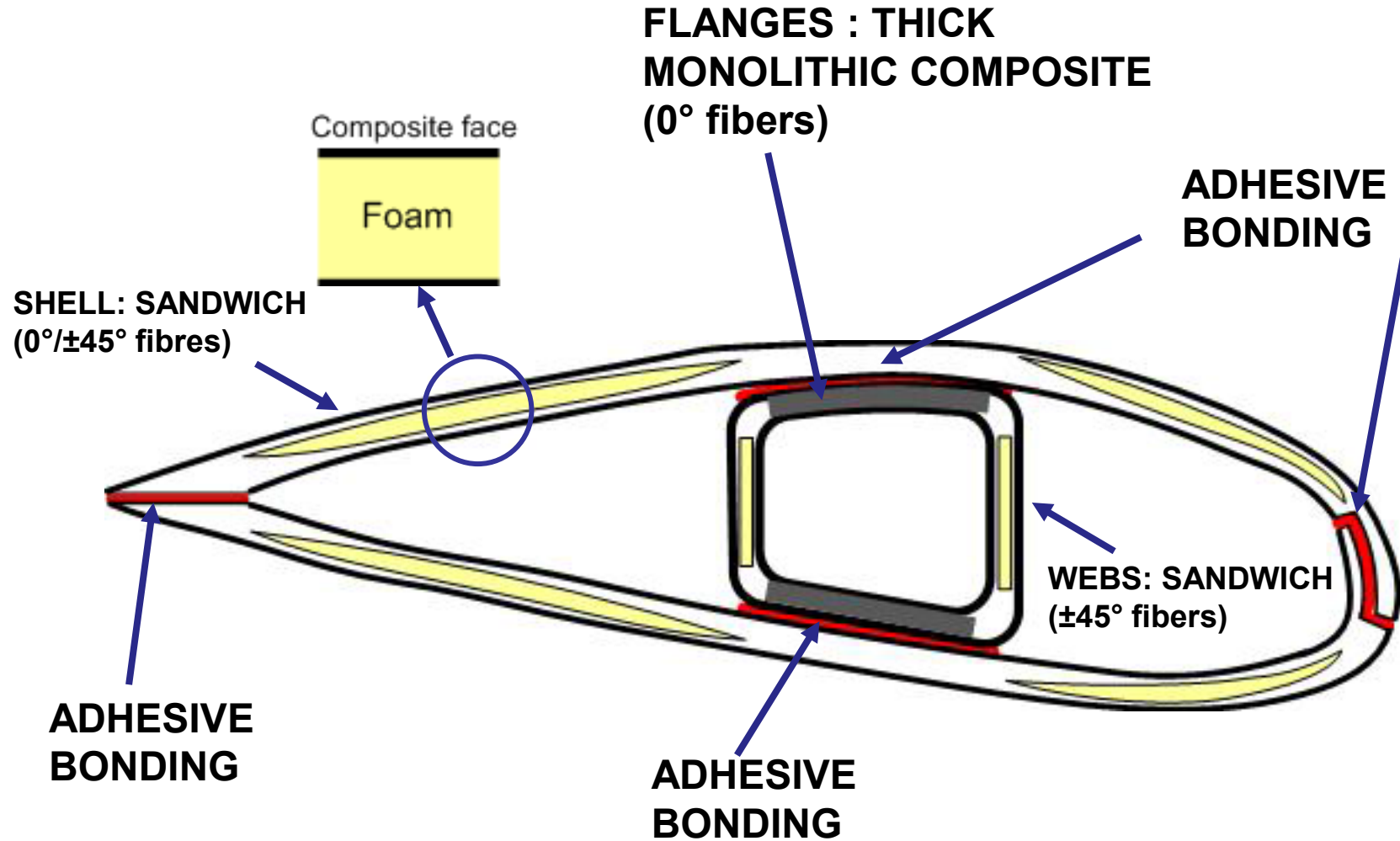
- consist of **different kinds of materials** (typically composite materials in monolithic or sandwich configuration)
- use **various connections solutions** between different substructures
- include **many material or geometric transitions**



Cross-section concepts: main spar

The two parts are bonded to a **load-carrying spar-beam** (box-beam)

The main spar and the wing shells are manufactured separately and then joined in a separate bonding process.

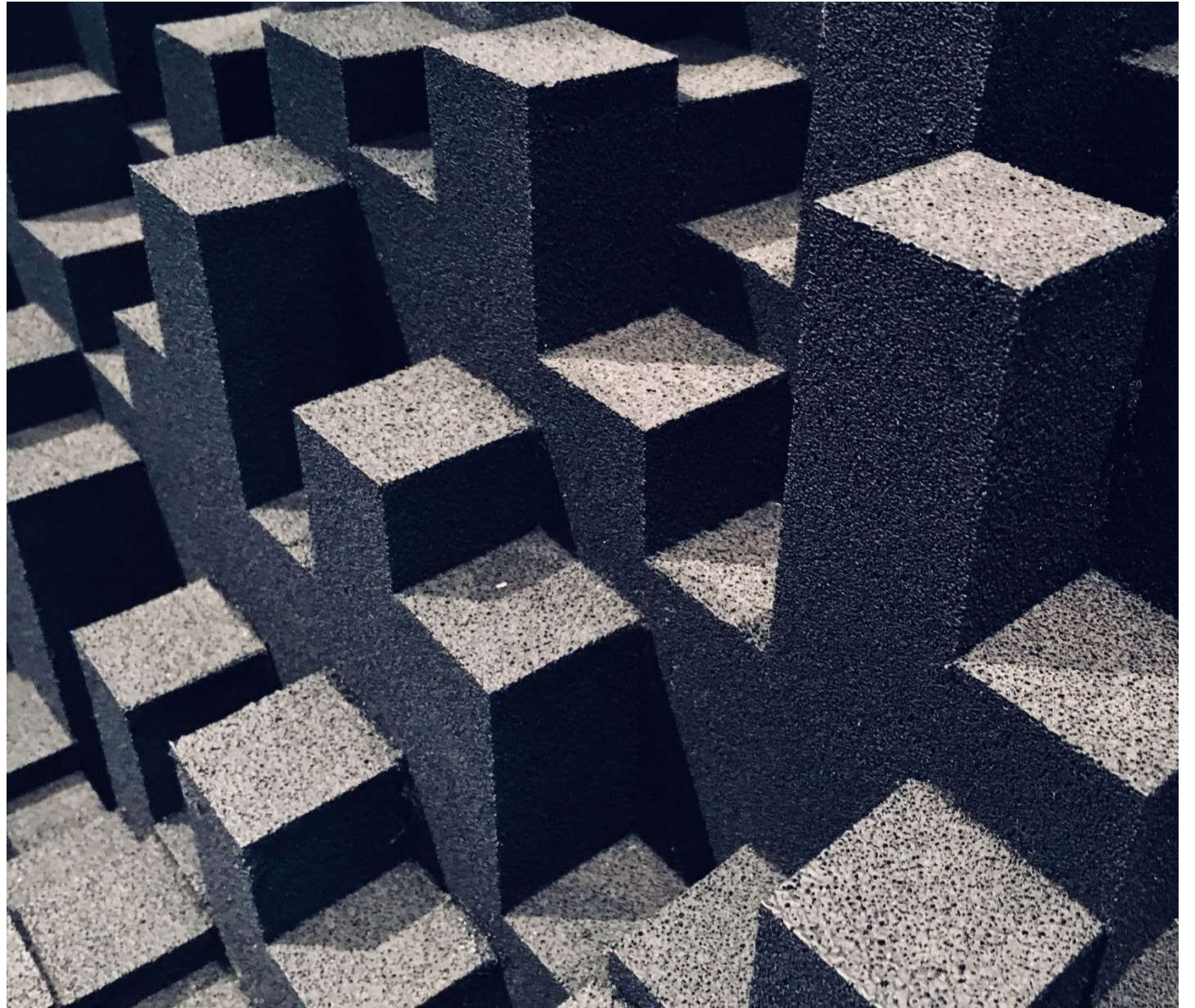


Technological advancements...

<https://www.compositesworld.com/news/aernnov-a-leonardo-and-afuzion-will-partner-with-radia-to-build-windrunner>



Perception and marketability



“New” materials for building construction: Synthetic polymers reinforced with fibers

House of the future, 1957 (California)



Pavilion “Les échanges”, Expo 1964 (Lausanne)



Market roof, 1967 (Argenteuil, France)



Futuro house, 1968 (Central Museum of Utrecht)



Experimental plastic house, Leningrad, 1962

[https://www.reddit.com/r/RetroFuturism/comments/skjjsj/soviet_individual_plastic_house from 1961 it was/](https://www.reddit.com/r/RetroFuturism/comments/skjjsj/soviet_individual_plastic_house_from_1961_it_was/)

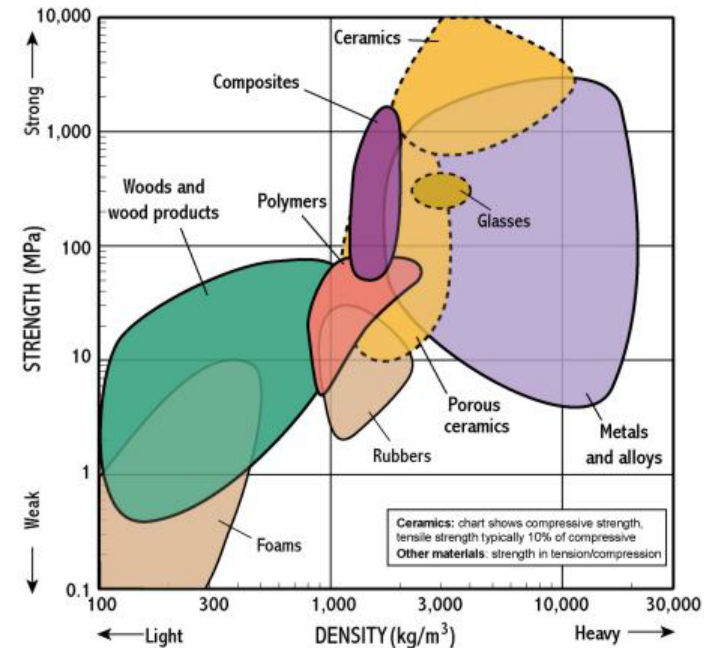
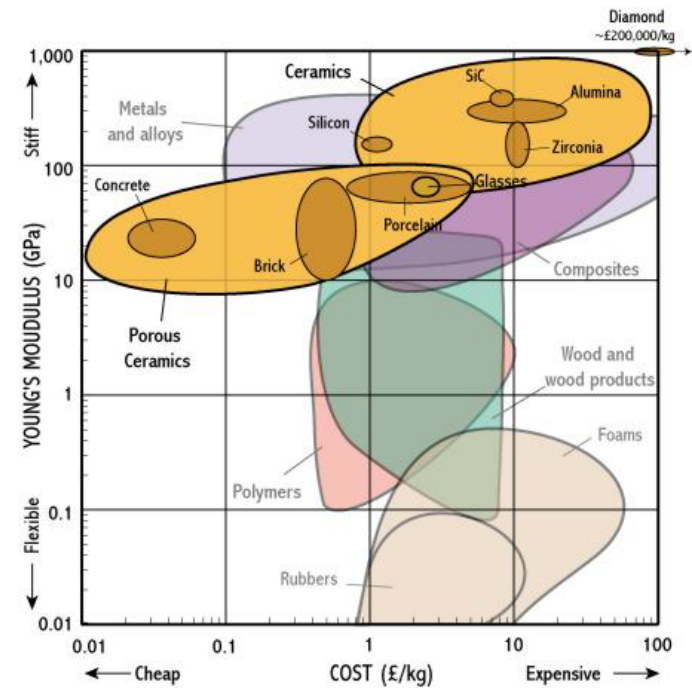
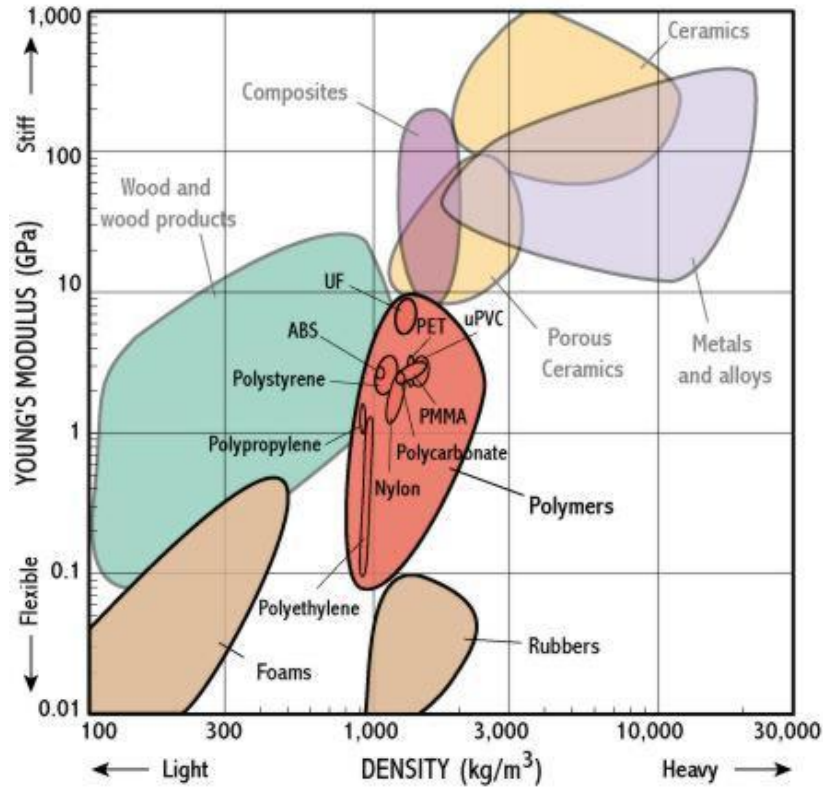


<http://www.bubblemania.fr/en/des-concepts-maisons-plastiques/>

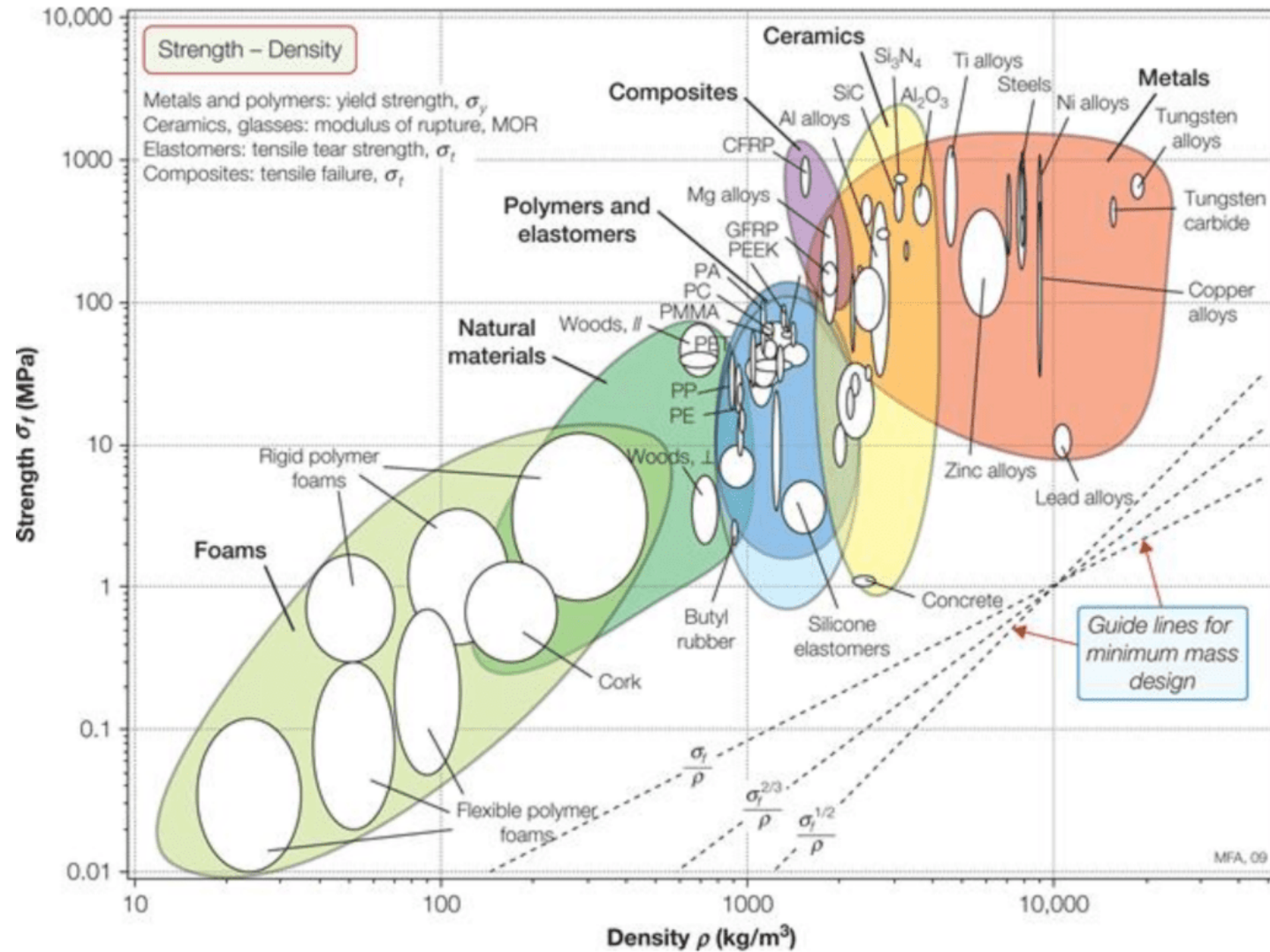
Characteristics of composite materials (design considerations)

- **Lightweight:** leads to fuel saving, increase in payload, or increase in range which improves performances.
- **Posses high strength and are elastic:** are extremely strong, especially per unit of weight. when composites are bent, they want to naturally snap back into place. This feature is ideal for springs and is why composites are used in car leaf springs and in the limbs of archery bows.
- **Good fatigue resistance:** leads to enhanced life which involves saving in the long-term cost of the product.
- **Good corrosion and chemical resistance:** means fewer requirements for inspection which results in saving on maintenance cost. This is why the marine industry was one of the first to adopt the use of composites.
- **Non-conductive:** Some composites, e.g. GFRP are non-conductive. This is important in some applications, e.g. ladders.

“Ashby plots” for comparison of materials



“Ashby plots” for comparison of materials



Characteristics of composite materials (design considerations)

- **Free formability**
 - Architectural aspect
 - New aesthetic possibilities
 - Geometrically more efficient solutions
- **Special surface finishes**
 - Integrate special finishes and unusual effects
 - Simulation of traditional materials: stone, granite...
- **Offsite fabrication and modular construction**
 - Better quality control
 - Faster built times
 - Manufacture concurrent with ground works on site

Characteristics of composite materials (design considerations)

- **Reduced mass**

- Easier, faster and more economic installation: Smaller cranes required
- Ability to bring larger sections on site: reducing assembly time and cost
- Less disruption during installation: Bridges...
- Reduction in size and cost of supporting structure, foundations, etc: City lifting, bridges
- Reduced energy in transportation to site

Characteristics of composite materials (properties)



Composite materials **do not yield** (their elastic limits correspond to the rupture limit).



They **age** subjecting to humidity (epoxy resin can absorb water by diffusion up to 6% of its mass; the composite of reinforcement/resin can absorb up to 2%).



They **do not corrode**, except in the case of contact "aluminum with carbon fibers" in which case galvanic phenomenon creates rapid corrosion.



Composite materials are **not sensitive to the common chemicals** used in engines: grease, oils, hydraulic liquids, paints and solvents, petroleum.



Have excellent **fire resistance** as compared with the light alloys with identical thicknesses. However, the smokes emitted from the combustion of certain matrices can be toxic.

Attractive composite characteristics

Specific stiffness

Strength

Low mass

Low cost
production of
complex shapes

Corrosion
resistance

Good fatigue
performance

Electrical
insulation

Good ballistic
performance

Low CTE

...

Fiber reinforced composites

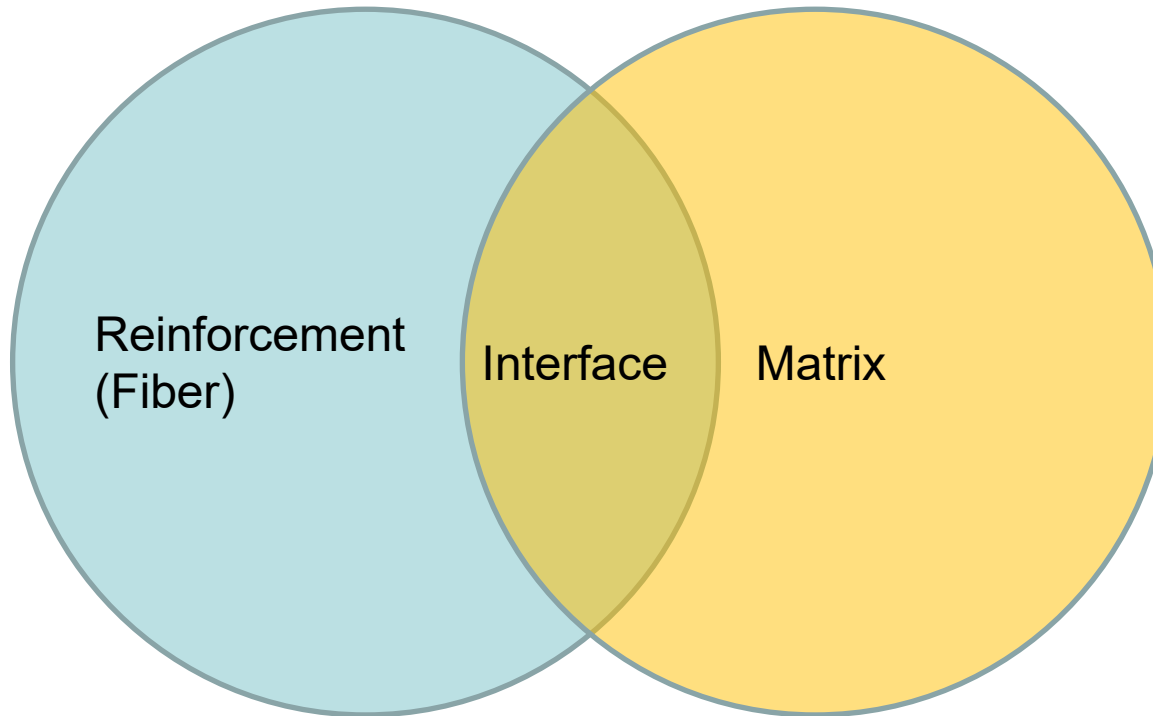
Consist of two components

- Fibers – Load currying component
- Matrix – keep fibers together and transfer load

The properties depend on: (Besides the type of the constituent material)

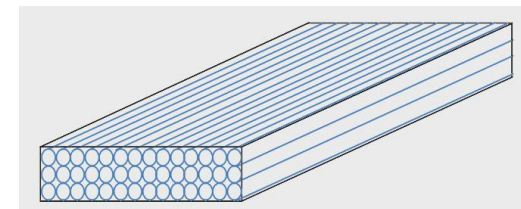
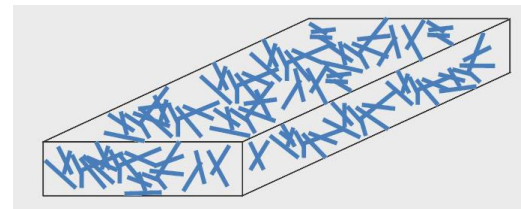
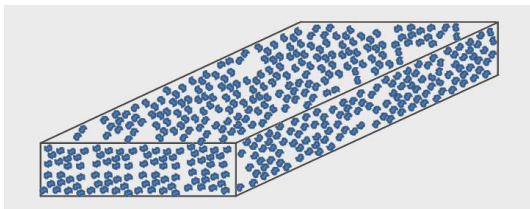
- The proportions of reinforcements and matrix (rule of mixtures)
- The form of the reinforcement (roving, mat etc.)
- The fabrication process

Composite Material concept



Roles:

- **Matrix**
 - Holds fibers in position
 - Protects the fibers
 - Transfers loads to and from the fibers
- **Fibers**
 - Load carrying components
 - Provide stiffness
- **Interface**
 - Transmits load between matrix and fibers
 - Minimizes ingress of corroding agents
 - Controls debonding



Typical fibre composite properties (65% fibre + 35% epoxy resin matrix)

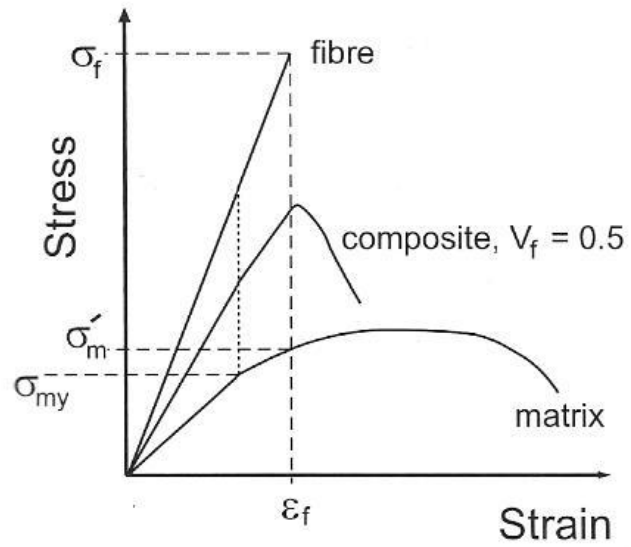
	Density ρ kg/m ³	Modulus E GPa	Strength σ^* MPa	E/ρ $\times 10^3$	σ^*/ρ $\times 10^3$
Carbon fibre (high modulus)	1700	222	1630	133	977
Carbon fibre (high strength)	1600	151	2080	93	1284
Kevlar 49	1400	82	1820	65	1300
E-glass	2100	50	1086	24	515
S-glass	2100	57	1358	27	644
Boron	2100	207	2210	97	1030
polyethylene	970	77	1700	79	1753

**“Specific”
mechanical
properties**

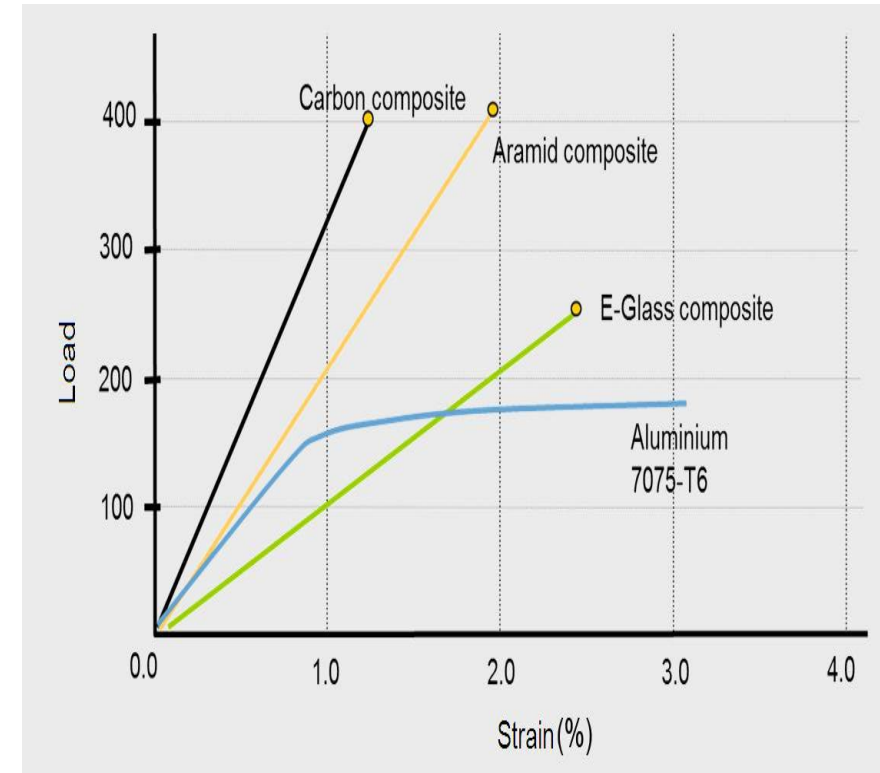
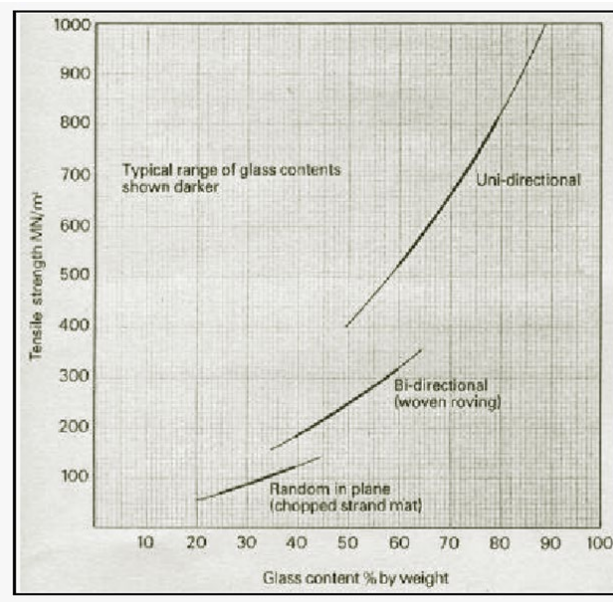
Some metals for comparison:

Mild steel	7900	210	450	27	57
Aluminium alloy	2800	70	450	25	161
Titanium	4500	110	960	24	213

Strength and stiffness of composites

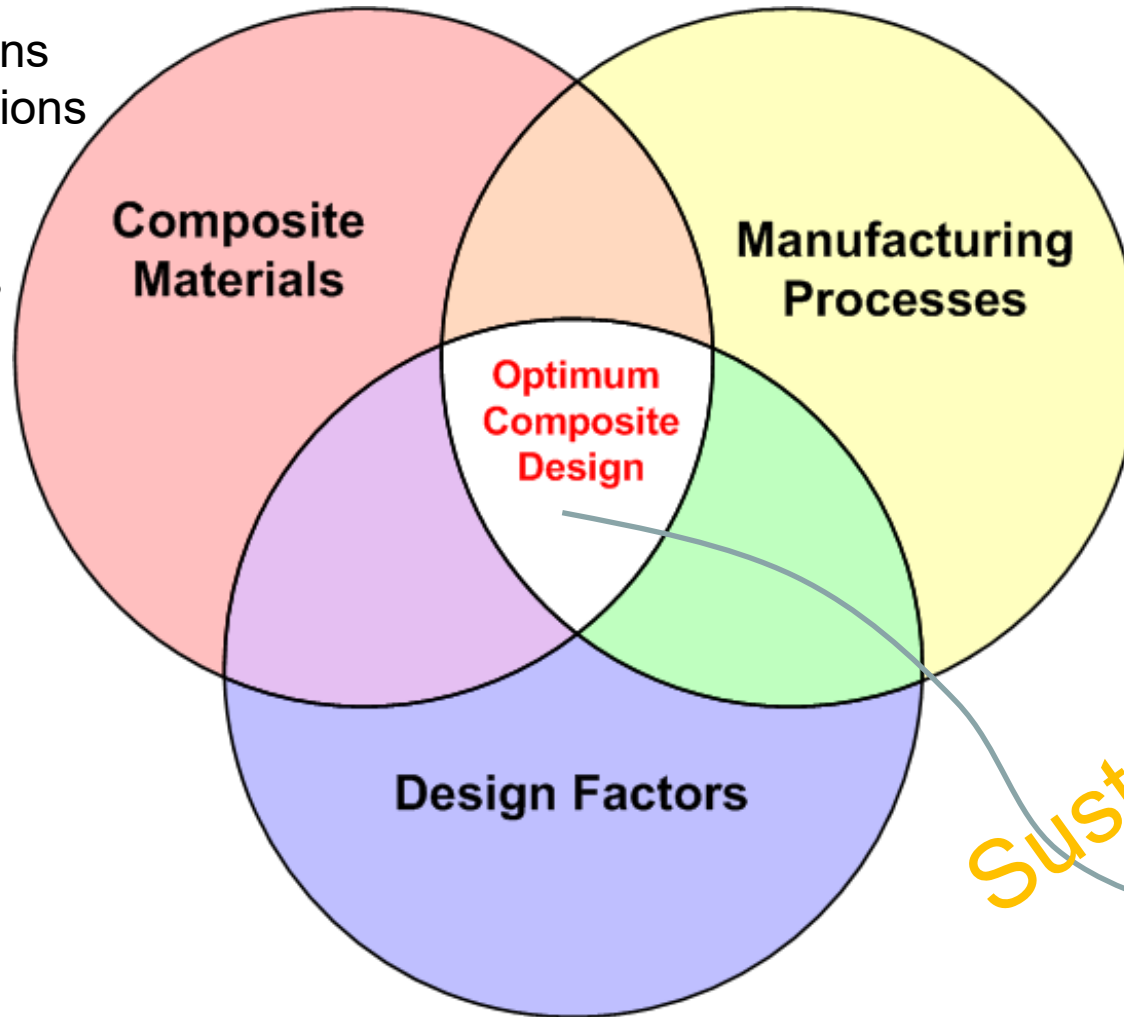


(a) Brittle-fibre/ductile-matrix



The challenge of composites

10+ fiber options
30+ matrix options
- Many
combination
considerations



10+ manufacturing
options
+ many process
variations - such as
tooling and
consolidation
options

Sustainability

Reuse?
Recycle?
Landfilling?
Incineration?

More complex design due to anisotropic materials, Link between manufacture, and material properties

Taylor made material!

Sustainability

Reduce

- Reduce the amount of the waste

Reuse

- Use materials repeatedly

Recycle

- Make new products after recycling of the material


Recover

- Recover energy from scrap


Landfill

- Safe disposal (?)


Fibers


 Principal fiber materials are


 Glass

 Carbon (high modulus or high strength)

 Aramid or Kevlar, (very light)

 Boron (high modulus or high strength)

 Silicon carbide (high temperature resistant)

 Basalt

Manufacturing of fibers



Glass fiber: The filaments are obtained by pulling the glass (silicon + sodium carbonate and calcium carbonate; $T > 1000^{\circ}\text{C}$) through the small orifices of plate made of platinum alloy.



Kevlar fiber: This is an aramid fiber, yellowish color, made by DuPont de Nemours (USA). These are aromatic polyamides obtained by synthesis at -10°C , then fibrillated and drawn to obtain high modulus of elasticity.

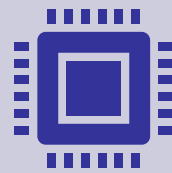


Carbon fiber: Filaments of polyacrylonitrile or pitch (obtained from residues of the petroleum products) are oxidized at high temperatures (300°C), then heated further to 1500°C in a nitrogen atmosphere. Black and bright filaments are obtained. High modulus of elasticity is obtained by drawing at high temperature.

Manufacturing of fibers

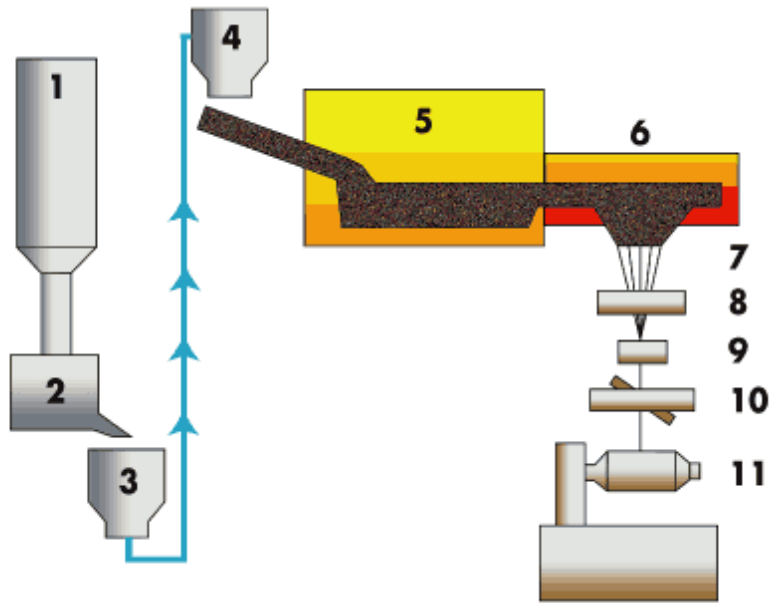


Boron fiber: Tungsten filament (diameter 12 mm) serves to catalyze the reaction between boron chloride and hydrogen at 1200°C. The boron fibers obtained have a diameter of about 100 μ m (the growth speed is about 1 micron per second).



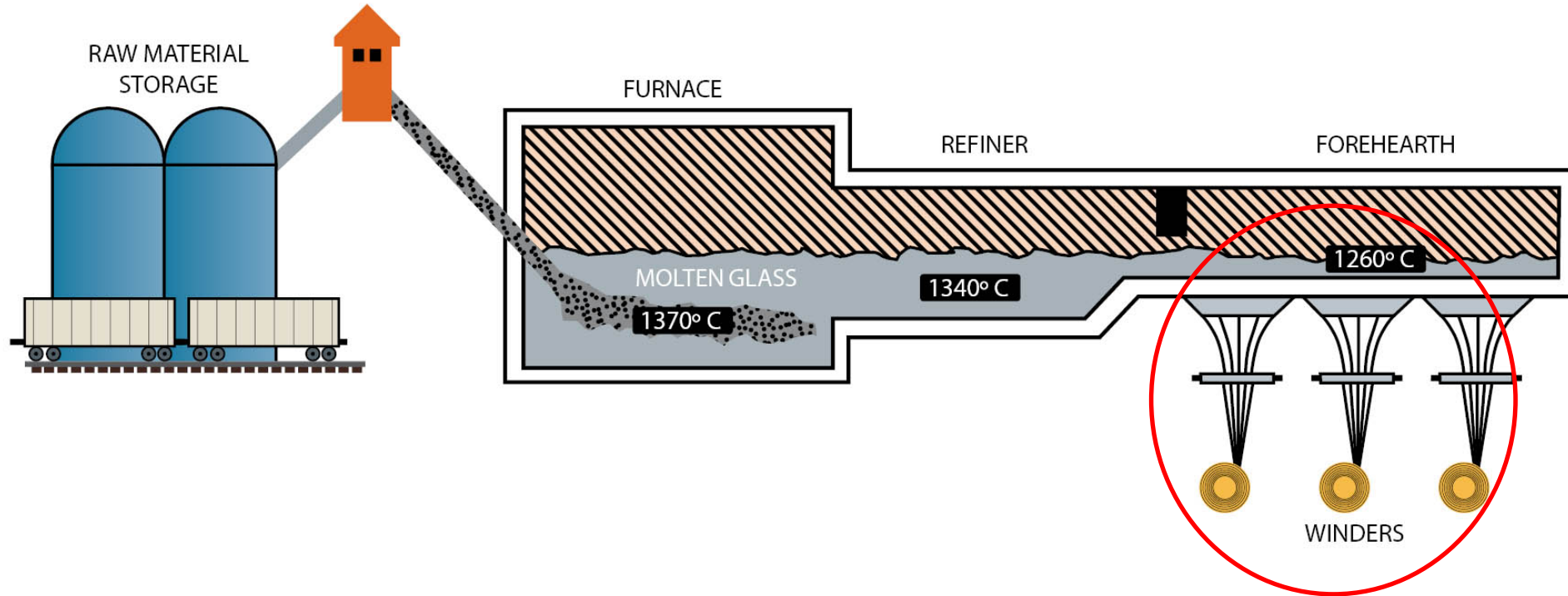
Silicon carbide: The principle of fabrication is analogous to that of boron fiber: chemical vapor deposition (1200°C) of methyl trichlorosilane mixed with hydrogen.

Production of Basalt fibers



1. Crushed stone silo
2. Loading station
3. Transport system
4. Batch charging station
5. Initial melt zone
6. Secondary heat zone with precise temperature control
7. Filament forming bushings
8. Sizing applicator
9. Strand formation station
10. Fiber tensioning station
11. Automated winding station.

Production of glass fibers



Production of glass fibers

Glass Fiber Mechanical Properties

	E-glass	R-glass	HS2,HS4	T-glass	S-1	S-2
Tensile Strength GPa	1.9-2.5	3.1-3.4	3.1-4.0	4.0-4.2	3.8-4.1	4.3-4.6
Tensile Modulus GPa	69-80	86-89	82-90	84	85-87	88-91

Composition of Selected Glass Fiber Types by Weight

	E-glass w/Boron	E-glass w/o Boron	ECR-glass	S-2 glass	R-glass	Quartz
SiO₂	52-56%	59%	54-62%	64-66%	60-65%	99.9999%
Al₂O₃	12-16%	12.1-13.2%	9-15%	24-26%	17-24%	-
B₂O₃	5-10%	-	-	-	-	-
CaO	16-25%	22-23%	17-25%	-	5-11%	-
MgO	0-5%	3.1-3.4%	0-5%	8-12%	6-12%	-
ZnO	-	-	2.9%	-	-	-
Na₂O	0-1%	0.6-0.9%	1.0%	0-0.1%	0-2%	-
K₂O	trace	0-0.2%	0.2%	-	0-2%	-
TiO₂	0.2-0.5%	0.5-1.5%	2.5%	-	-	-
Zr₂O₃	-	-	-	0-1%	-	-
Li₂O	-	-	-	-	-	-
Fe₂O₃	0.2-0.4%	0.2%	0.1%	0-0.1%	-	-
F₂	0.2-0.7%	0-0.1%	trace	-	-	-

Glass fibers

Short fibers, with lengths of a few centimetres or fractions of millimetres are **felts, mats**, and short fibers used in injection moulding.

Long fibers, which are cut during time of fabrication of the composite material, are used as they are or as woven fabric



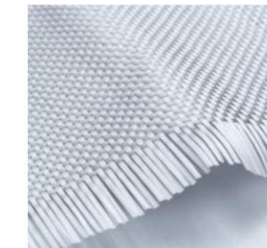
Roving



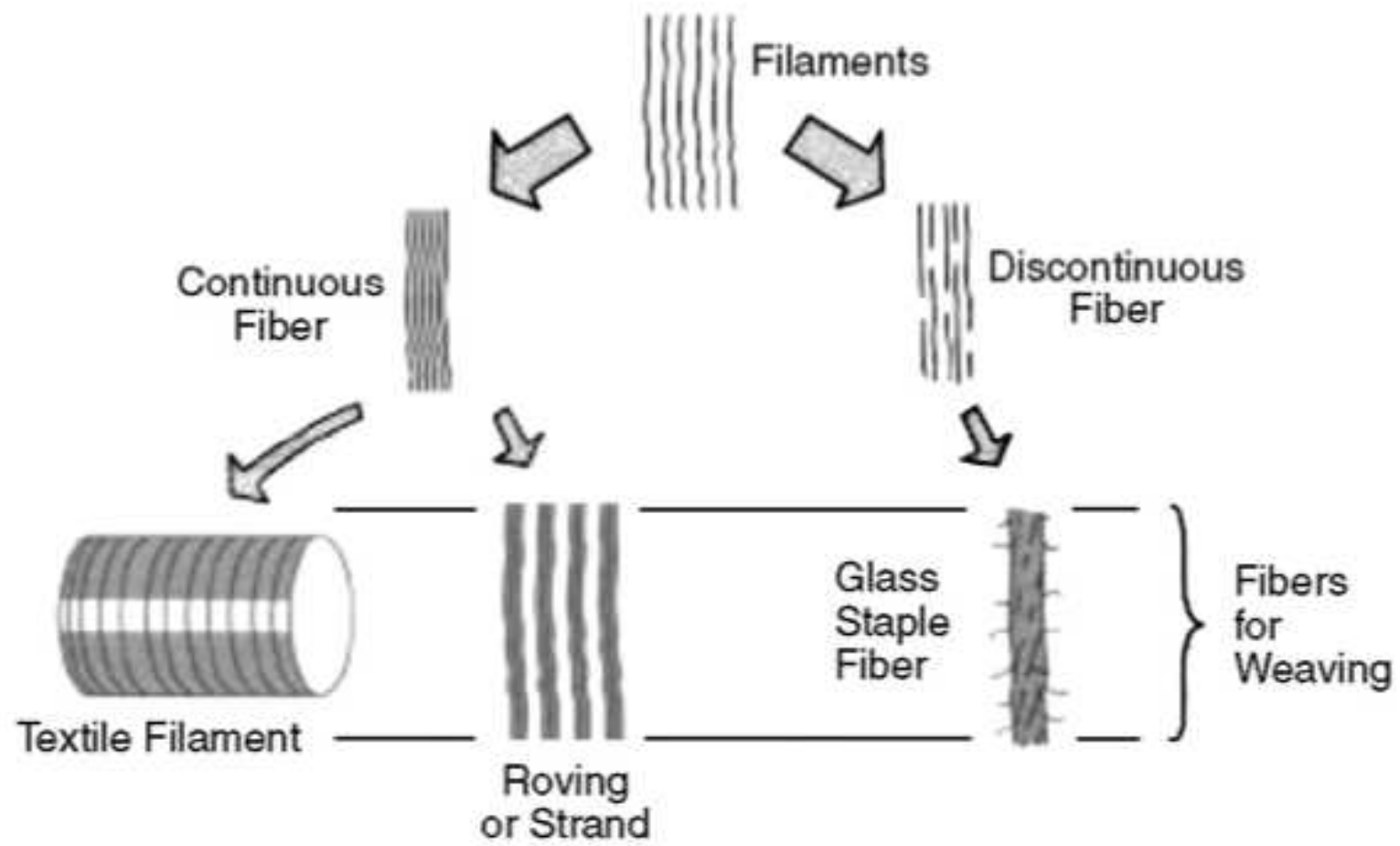
Yarn



Chopped strand Mat



Fabric



Properties of commonly used reinforcements

<i>Reinforcements</i>	<i>Fiber Diameter</i> $d(\mu\text{m})$	<i>Density</i> $\rho(\text{kg/m}^3)$	<i>Modulus of Elasticity</i> $E(\text{Mpa})$	<i>Shear Modulus</i> $G(\text{Mpa})$	<i>Poisson Ratio</i> ν	<i>Tensile Strength</i> $\sigma_{Ult} (\text{Mpa})$	<i>Elongation</i> $E(\%)$
"R" glass, high performance	10	2500	86,000		0.2	3200	4
"E" glass, common applications	16	2600	74,000	30,000	0.25	2500	3.5
Kevlar 49	12	1450	130,000	12,000	0.4	2900	2.3
"HT" graphite, high strength	7	1750	230,000	50,000	0.3	3200	1.3
"HM" graphite, high modulus	6.5	1800	390,000	20,000	0.35	2500	0.6
Boron	100	2600	400,000			3400	0.8
Aluminum	20	3700	380,000			1400	0.4
Aluminum silicate	10	2600	200,000			3000	1.5
Silicon carbide	14	2550	200,000			2800	1.3
Polyethylene		960	100,000			3000	

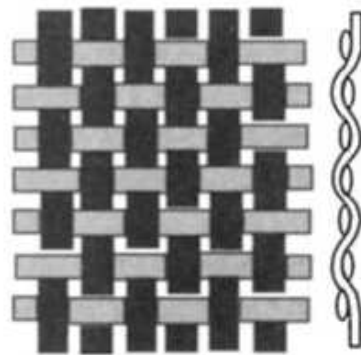
Fiber reinforcements

In forming fiber reinforcement, the assembly of fibers to make fiber forms for the fabrication of composite material can take the following forms:

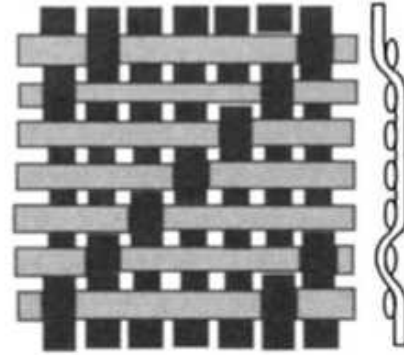
Unidirectional: unidirectional tows, yarns, or tapes

Bidirectional: woven or nonwoven fabrics (felts or mats)

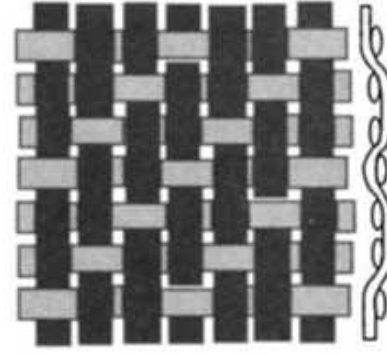
Tridirectional: fabrics (sometimes called *multidirectional fabrics*) with fibers oriented along many directions (>2)



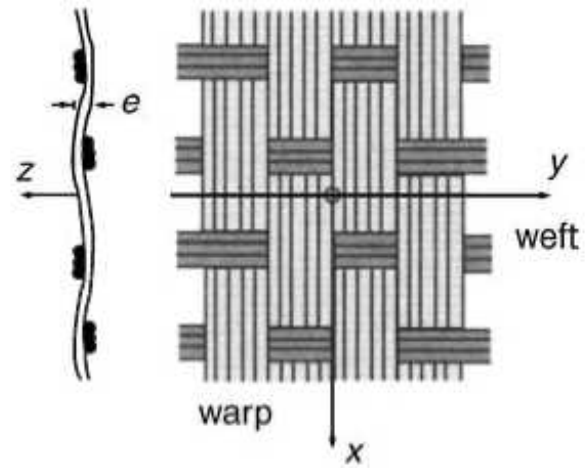
a) plain weave



b) satin weave



c) twill weave



Carbon fiber demands

Table 3	Carbon Fiber Demand Forecast, Aerospace and Defense, metric tonnes		
	2011	2015	2020
Commercial aircraft	4,300	7,910	13,290
Military fixed-wing	500	770	1,000
Rotorcraft	370	400	460
Business Aircraft	240	590	720
General Aviation	600	1,000	1,250
Jet engines	380	1,660	1,930
Space and launch	450	520	550
Carbon-carbon	160	240	500
Total:	7,000	13,100	19,700

Table 4	Carbon Fiber Demand Forecast, Industrial, metric tonnes		
	2011	2015	2020
Wind energy	12,280	37,600	67,400
Oil and gas	1,380	2,700	10,650
Molding compounds	5,750	7,700	10,170
Industrial rollers	450	700	820
Pressure vessels	1,650	7,250	12,520
Automotive	2,700	4,000	5,600
Civil infrastructure	1,900	2,900	3,900
Pultrusion	1,300	2,200	3,710
Misc. energy	180	500	1,520
Medical/prosthetics	240	320	440
Tooling	2,000	2,700	3,960
Total:	29,830	68,570	120,690

Matrices



Polymeric matrix: thermoplastic resins (polypropylene, polyphenylene, sulfone, polyamide, polyetheretherketone, etc.) and thermoset resins (polyesters, phenolics, melamines, silicones, polyurethanes, epoxies).



Mineral matrix: silicon carbide, carbon. Can be used at high temperatures



Metallic matrix: aluminum alloys, titanium alloys



Ceramic matrix: Boron nitride, boron carbide...

Properties of commonly used matrices

Table 1.4 Properties of Commonly Used Resins

<i>Resins</i>	<i>Density</i> ρ (kg/m ³)	<i>Elastic Modulus</i> <i>E</i> (Mpa)	<i>Shear Modulus</i> <i>G</i> (Mpa)	<i>Poisson Ratio</i> ν	<i>Tensile Strength</i> σ_{Ult} (Mpa)	<i>Elongation</i> <i>E</i> %
					<i>Thermosets</i>	
Epoxy	1200	4500	1600	0.4	130	2 (100°C) 6 (200°C)
Phenolic	1300	3000	1100	0.4	70	2.5
Polyester	1200	4000	1400	0.4	80	2.5
Polycarbonate	1200	2400		0.35	60	
Vinylester	1150	3300			75	4
Silicone	1100	2200		0.5	35	
Urethane	1100	700 to 7000			30	100
Polyimide	1400	4000 to 19,000	1100	0.35	70	1
					<i>Thermoplastics</i>	
Polypropylene (pp)	900	1200		0.4	30	20 to 400
Polyphenylene sulfone (pps)	1300	4000			65	100
Polyamide (pa)	1100	2000		0.35	70	200
Polyether sulfone (pes)	1350	3000			85	60
Polyetherimide (pei)	1250	3500			105	60
Polyether-ether-ketone (peek)	1300	4000			90	50

Polymeric matrices

Thermoset materials are obtained from a chemical reaction between the resin and the hardener to form a hard infusible product.

Polyester : easy to process (does not require post curing), inexpensive

Vinyl ester : cost and strength intermediate between polyester and epoxy

Epoxy : best mechanical properties, less shrinkage, expensive

Advantages	Disadvantages
Easy to process	Long curing times – Limited toughness Exotherm during curing (thick components)

Thermoplastic materials soften and melt with heating, then hardening again with cooling. The softening process can be repeated without any significant degradation of the material properties.

PP or L-PET: used in film or fibre form and consolidated by heating and vacuum

Reactive thermoplastics (APA-6): suitable for liquid moulding (similar to thermosets)

Advantages	Disadvantages
High toughness - Recyclability	High process temperature and pressure

Polymeric matrices

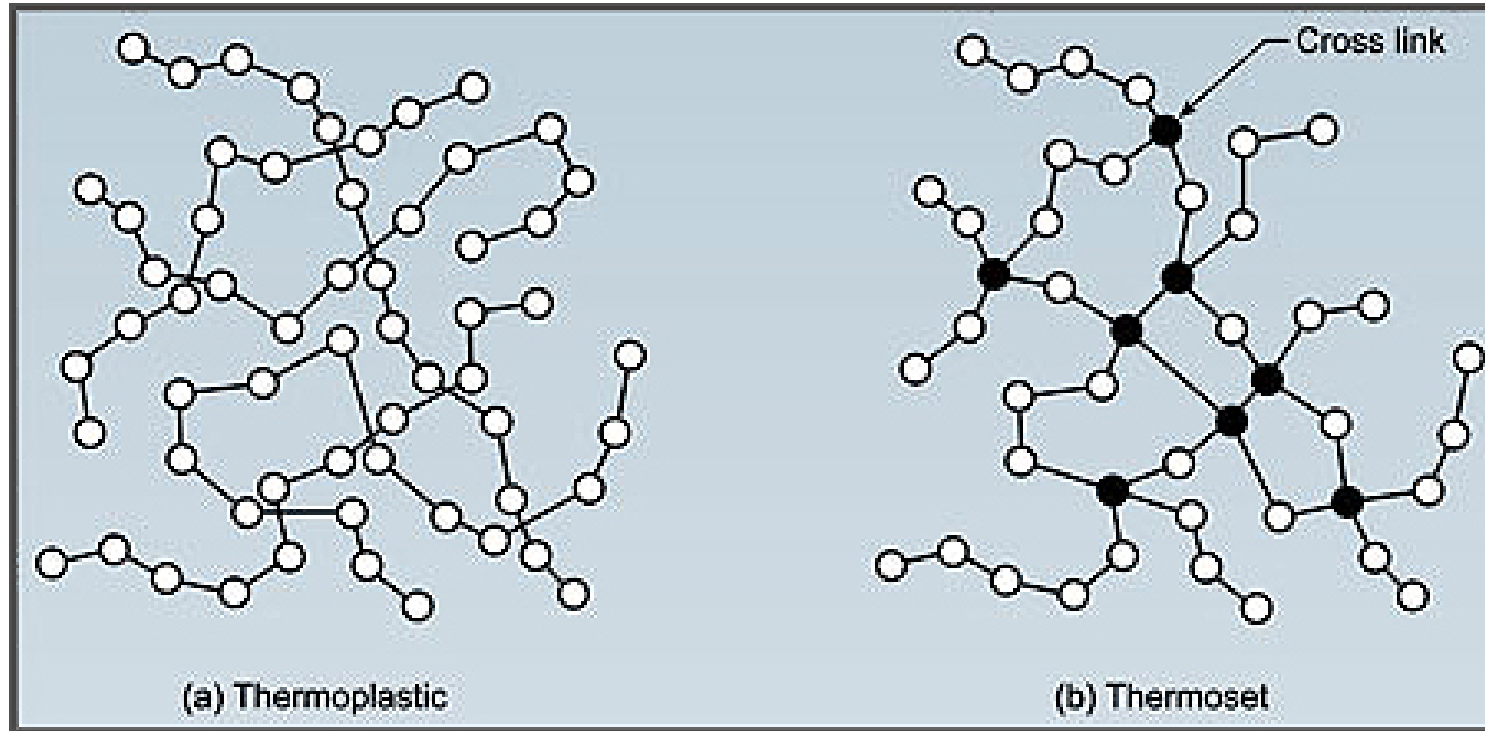
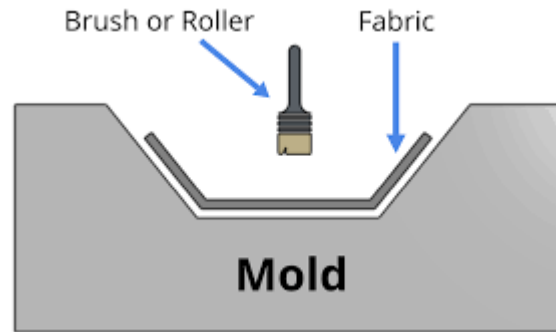


Image source: <https://www.recycledplastic.com/index.html%3Fp=10288.html>

Manufacturing

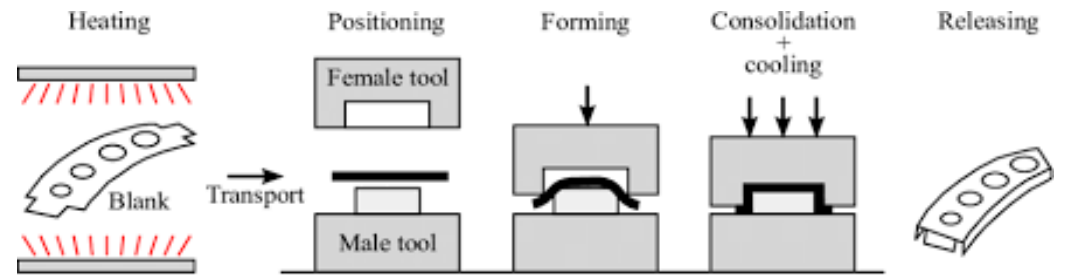


Methods for composites' manufacturing



Molding processes

Material is placed in a mould...



Forming processes

Material is passing through a mold to take the final shape...

Molding processes



Contact molding (Hand lay-up)



Compression molding



Vacuum molding



Injection molding



Foam injection molding



molding of components of revolution



...

Forming processes



Sheet forming



Profile forming (Pultrusion)



Stamp forming



Pre-forming by three-
dimensional assembly

Impregnation using liquid
Impregnation using gas

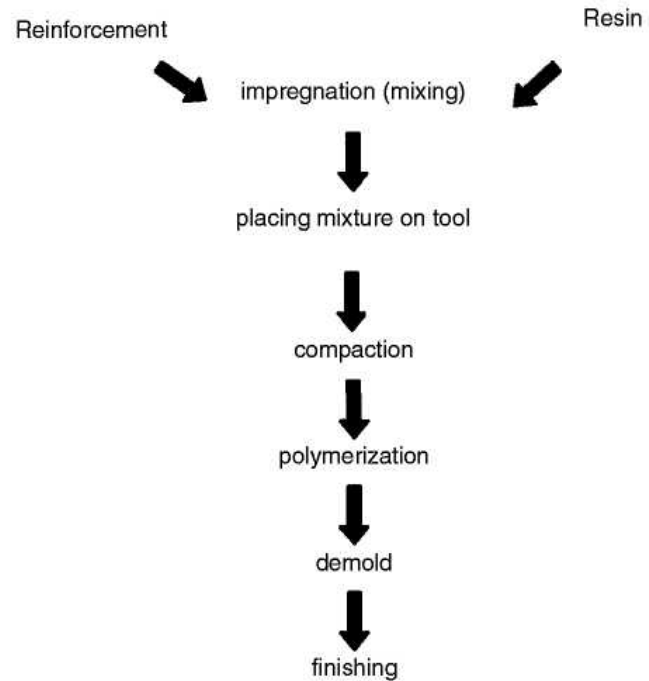


Cutting of fabric and trimming of laminates



...

Molding processes



Forming by molding processes varies depending on the nature of the part, the number of parts, and the cost. The mold material can be made of metal, polymer, wood etc, but in many cases is made by the same material as the component

Steps in Molding Process

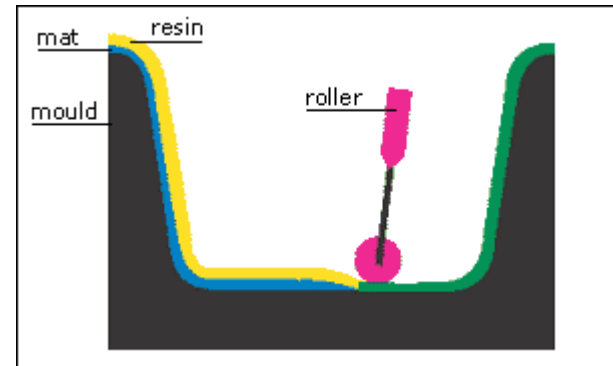


Molding process (hand lay-up)

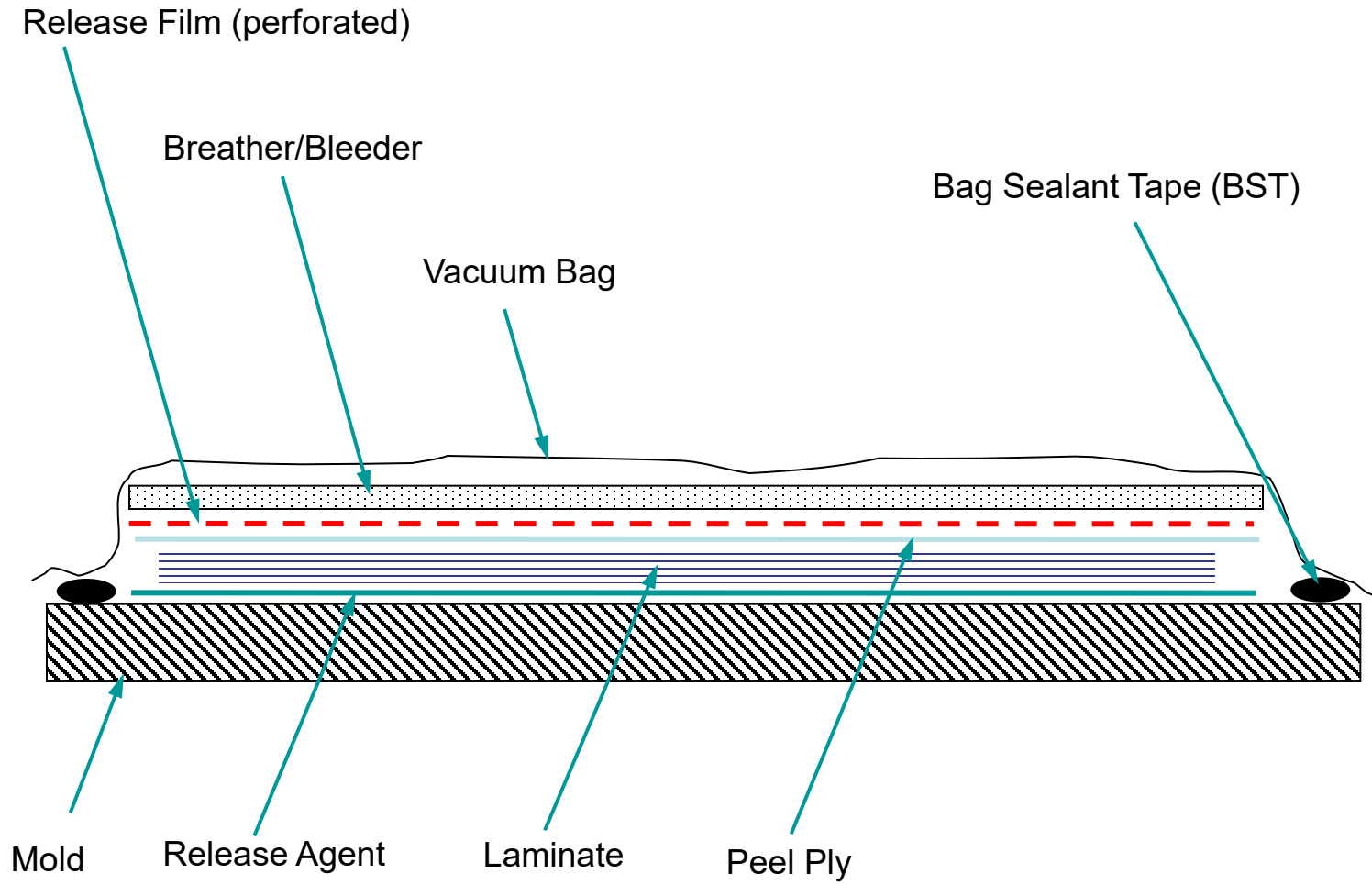


Contact Molding

It is recommended for small and medium volumes, for which the investment in moulds and equipment should not be very high.



Vacuum Bag Molding



Vacuum molding

Is applied under a piece of plastic. The piece is compacted due to the action of atmospheric pressure, and the air bubbles are eliminated. Porous fabrics absorb excess resin. The entire material is polymerized by an oven or by an **autoclave** under pressure to obtain better mechanical properties.

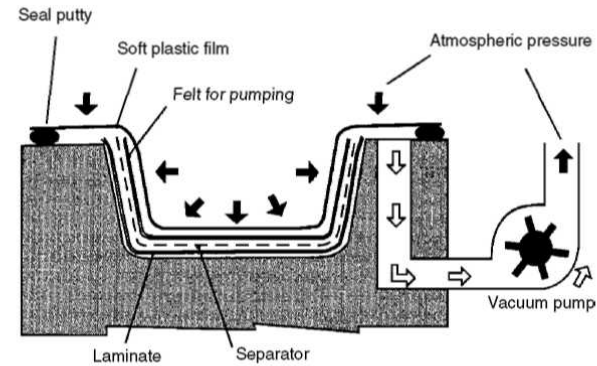
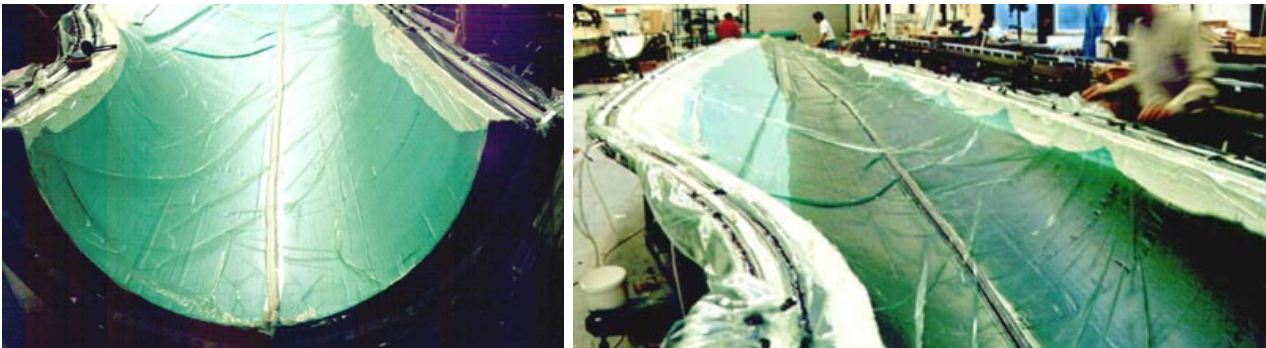


Figure 4.7 Vacuum Molding



Resin injection molding

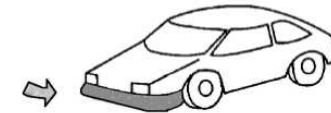
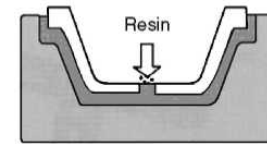
Injection molding

The process is used to produce large quantities of identical plastic items. One of the most common types of **thermoplastics** used in injection molding is **high impact polystyrene (HIPS)**.

Injection molding is the most important plastics manufacturing process.

It produces such small products as bottle tops; sink plugs, children's toys, containers, model kits, disposable razors and parts of cameras.

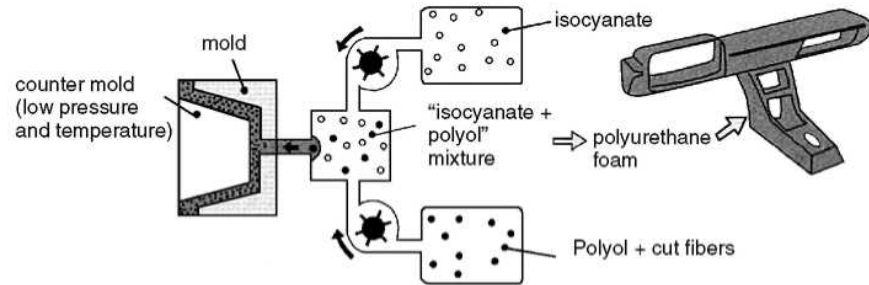
It is also used to manufacture larger items such as dustbins, and milk crates.



Resin Injection Molding

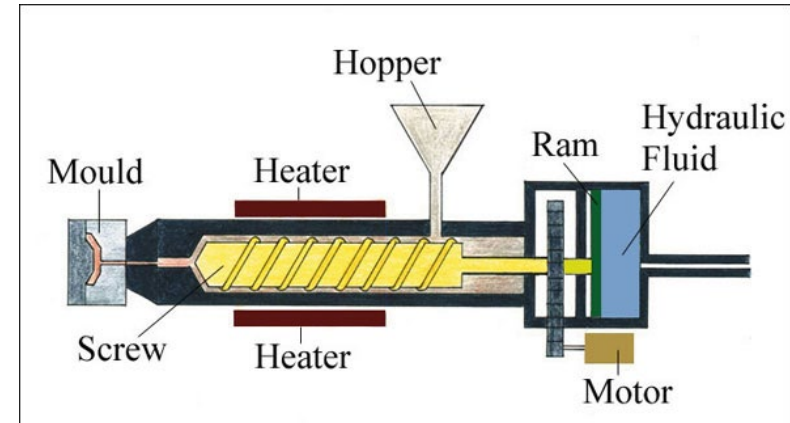


Structural foam injection



Foam Injection

Structural foam molding is a derivative of the injection molding process. Large structural parts often require thicker walls than standard injection molding can produce. Structural foam molding allows for the injection molding of thick wall parts through the addition of a foam agent, thus the term structural foam molding. Any injection moldable thermoplastics can be structurally foam moulded.



Other molding processes

Bottles and containers

Automotive fuel tanks

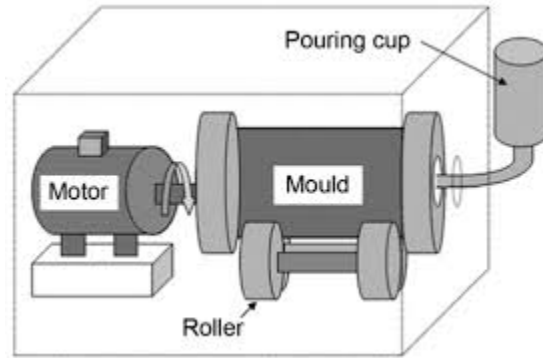
Venting ducts

Watering cans

Boat fenders etc

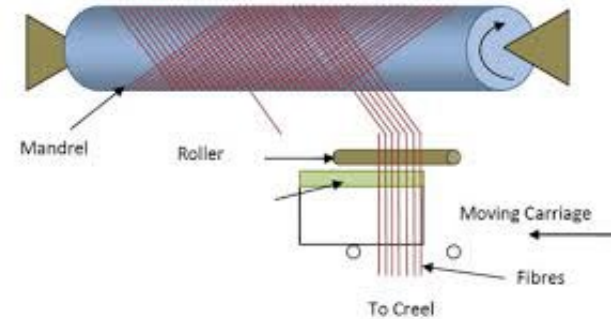


Molding of components of revolution



Centrifugal molding

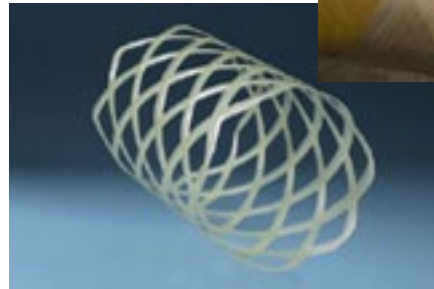
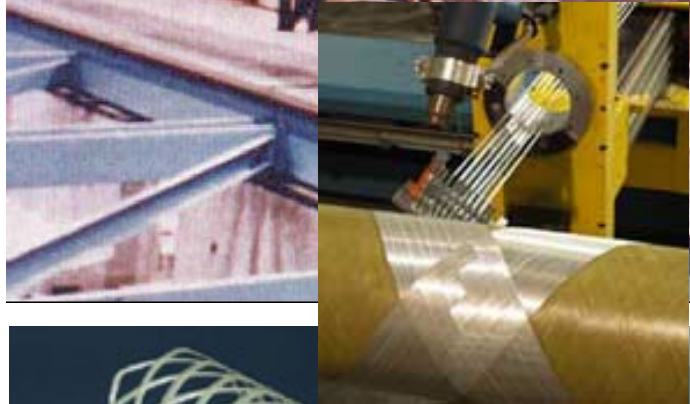
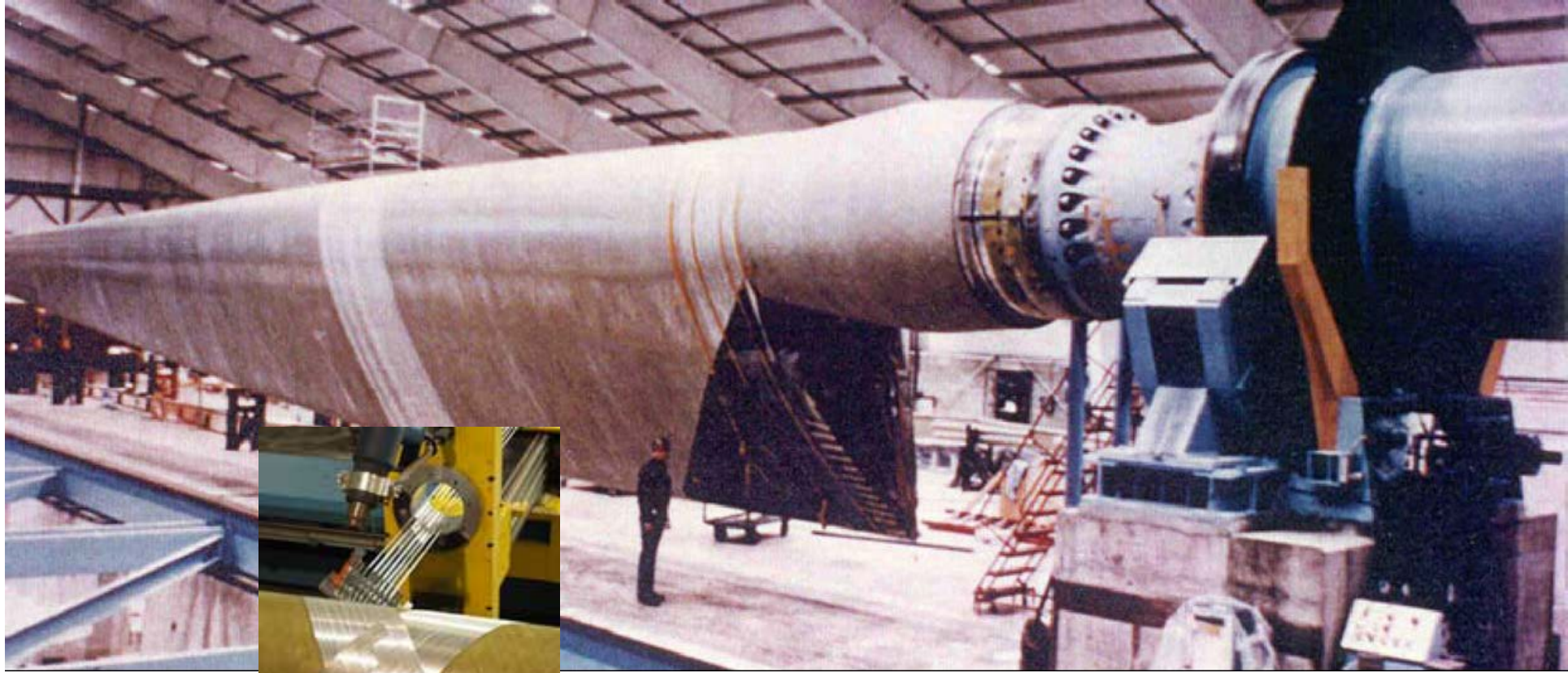
Fabrication of tubes. Allows homogeneous distribution of resin with good surface conditions



Filament winding

Can be integrated into a continuous chain of production and can fabricate tubes of long length.

For pieces which must revolve around their midpoint, winding can be done on a mandrel...



Filament winding

<https://www.youtube.com/watch?v=x8Bu-ZWVUwE>

Sheet forming/vacuum forming

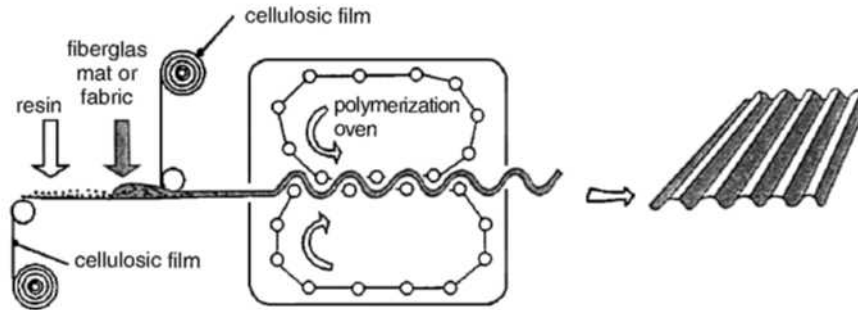
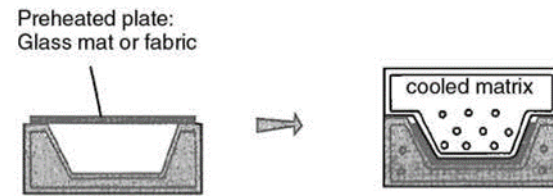


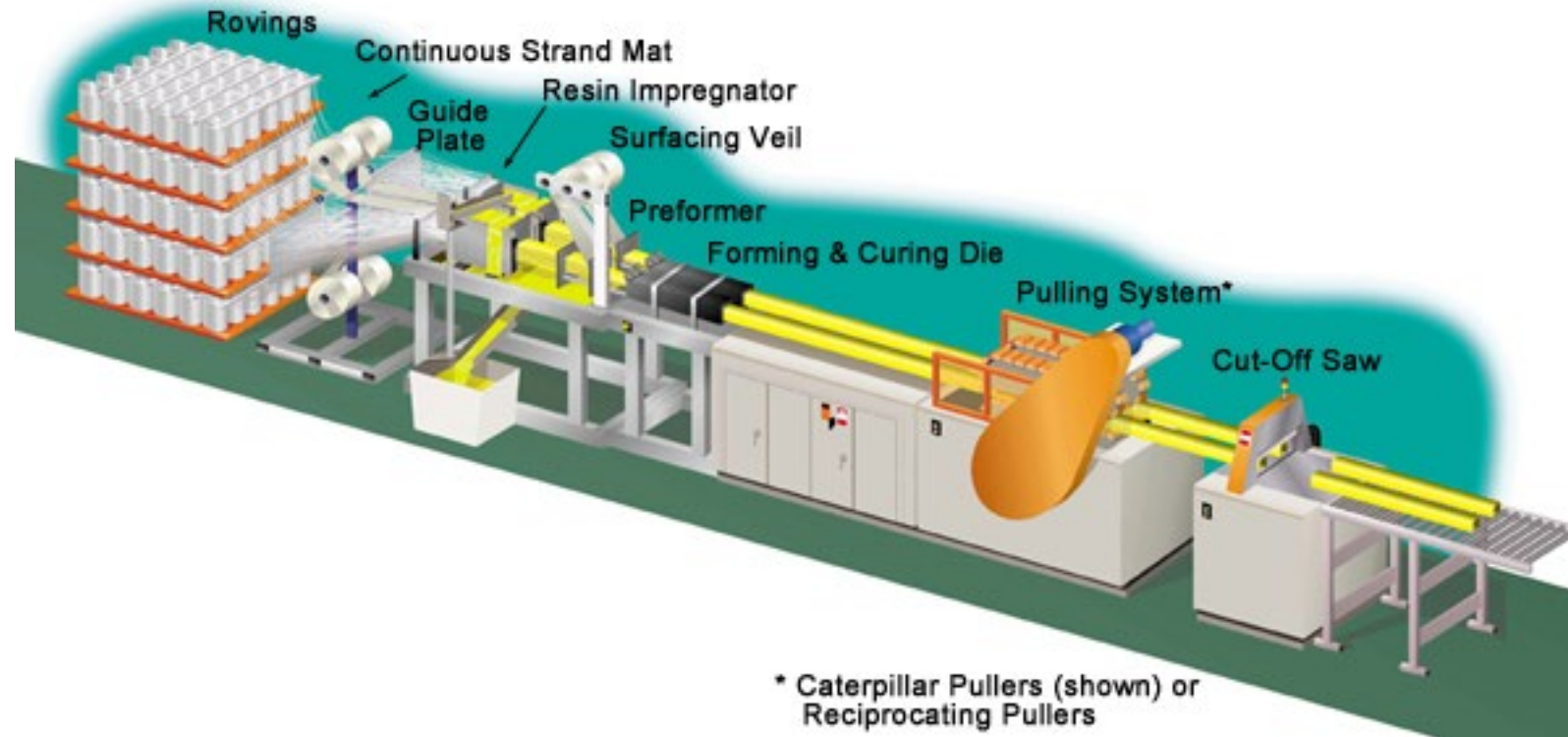
Figure 2.13 Sheet Forming



Stamp Forming



Profile forming (Pultrusion)



Interesting videos - sources



NASA 360 –
Composite
materials

<https://www.youtube.com/watch?v=tZhH2B-E11I>



Composite
materials intro by
JEC

<https://www.youtube.com/watch?v=dbywZ4PJ3QA>



Carbon Fiber
Construction -
/Inside Koenigsegg

https://www.youtube.com/watch?v=504I_hJDFck

Interesting videos and links

Vacuum bagging process

<https://www.youtube.com/watch?v=jfuaQK5YdeU>

pultrusion

https://www.youtube.com/watch?v=4MoHNZB5b_Y

Filament winding

<https://www.youtube.com/watch?v=wcdBTq2TpPc>

<https://www.youtube.com/watch?v=1A3vaJaNDLY>

<https://www.youtube.com/watch?v=PGGiuaQwcd8>

https://www.youtube.com/watch?v=504I_hJDFck

Carbon vs. Glass vs. Kevlar for automotive applications

<https://www.youtube.com/watch?v=KHXVf0SaJpA>

Links

<https://german-advanced-composites.com/>

<http://compositeslab.com/>