Composite materials for wind turbine blades

Wind turbine blades

Wind turbine blades are complex structures whose design involves the two basic aspects of

- Selection of the aerodynamic shape
- Structural configuration and materials selection (to ensure that the defined shape is maintained for the expected life)

Modern blades

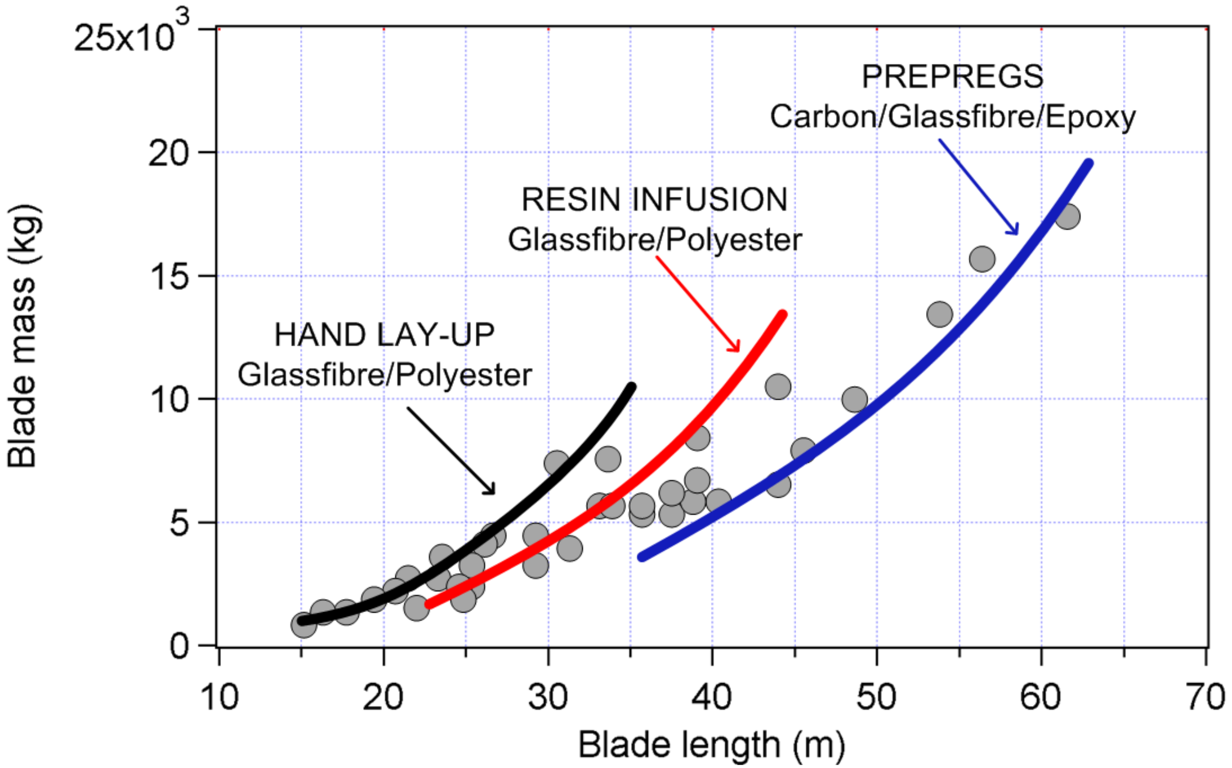
- consist of **different kinds of materials** (typically composite materials in monolithic or sandwich configuration)
- use **various connections solutions** between different substructures
- include **many material or geometric transitions**

Growth of blade mass with blade length

The growth rate of blade mass with length has been reducing in the past decades

Key drivers for reduction:

- **Improved manufacturing processes**
- **Introduction of new materials**
- **More efficient use of materials and improved structural configurations**



[Lekou, 2010]

Main loads on blades

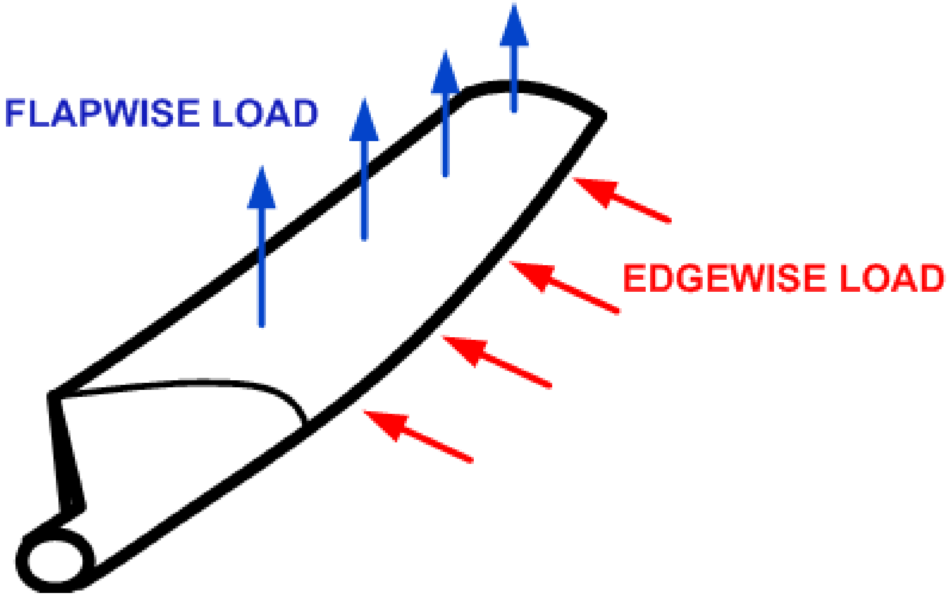
The main loads on the blades are generated by wind and by gravity.

Wind loads mainly induce both *flapwise* and *edgewise bending*.

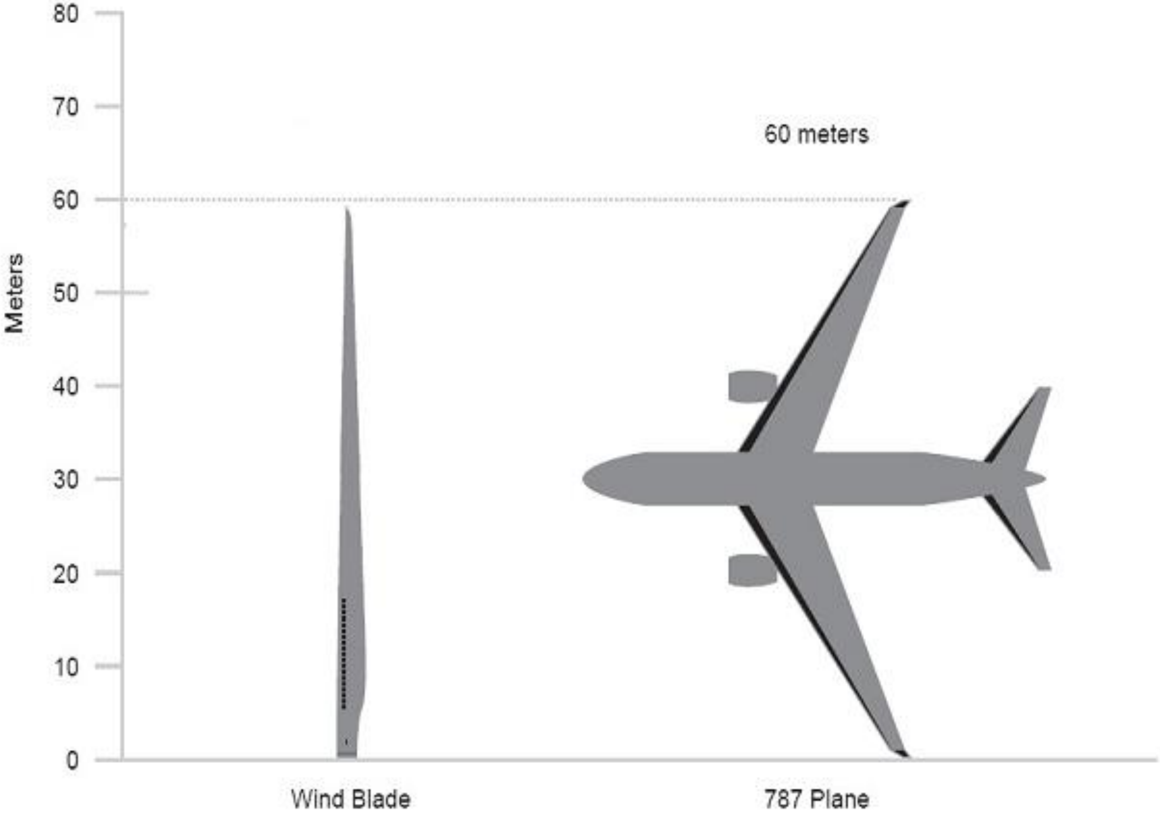
These loads have both a static and a dynamic component (variations in wind speed and natural wind shear) that induce fatigue on the blade material.

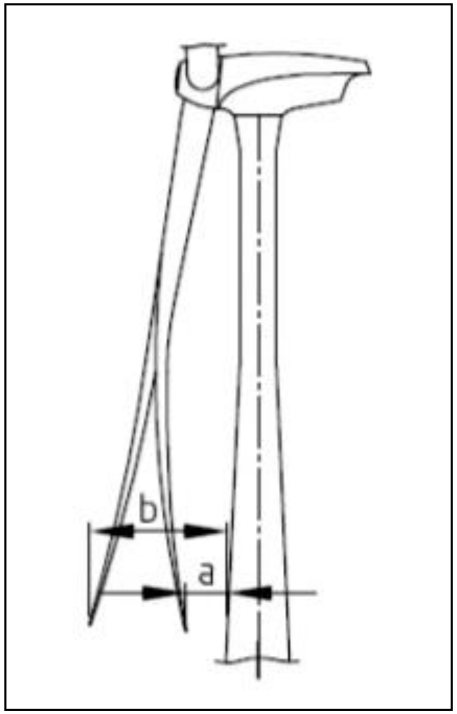
Gravity loads mainly induce edgewise bending, when the blade is horizontal.

The rotation of the blades cause alternating edge-wise bending and thus fatigue of the material.



Wind blade scale





High blade stiffness
to avoid collision with tower

Key structural design requirements

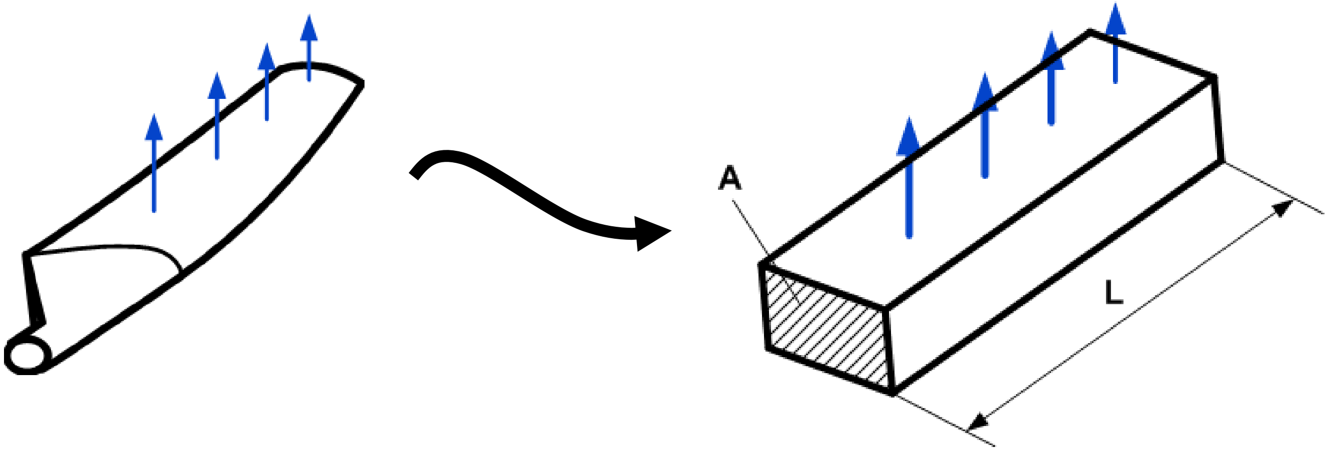
- the blades must be strong to **resist the extreme (ultimate) loads**;
- the blades must **resist the time-varying (fatigue) loads** through the entire life of the blade**;**
- the blades must be **stiff** to prevent collision with the tower under extreme loads. Local stiffness must be also sufficient to prevent instability of components under compression (to avoid local or global buckling)
- the blade construction needs to be as **light** as possible to minimize the cost of generated power
- the blades should be **stiff and light** to avoid resonance

Materials requirements

The structural design requirements translate to the following materials requirements in terms of **material properties**:

- **High material strength** is needed to withstand the extreme loads
- **High fatigue strength** is needed to resist varying loads and reduce material degradation during service
- **High material stiffness** is needed to maintain aerodynamic shape of the blade, to prevent collision with the tower, and to prevent local instability (buckling) under compressive loads
- **Low density** is needed to reduce gravity forces and to minimize the cost of power

Why composite materials on blades?



MATERIAL INDEX

Mass of the beam $m = AL\rho$

Stiffness of the beam $S = \frac{F}{\delta} = k\frac{EI}{L^3}$

$$\left.\begin{array}{l} m = AL\rho \\ S = \frac{F}{\delta} = k\frac{EI}{L^3} \end{array}\right\} \quad m = \left(\frac{12S}{kL}\right)^{1/2}\left(L^3\right)\left(\frac{\rho}{E^{1/2}}\right)$$

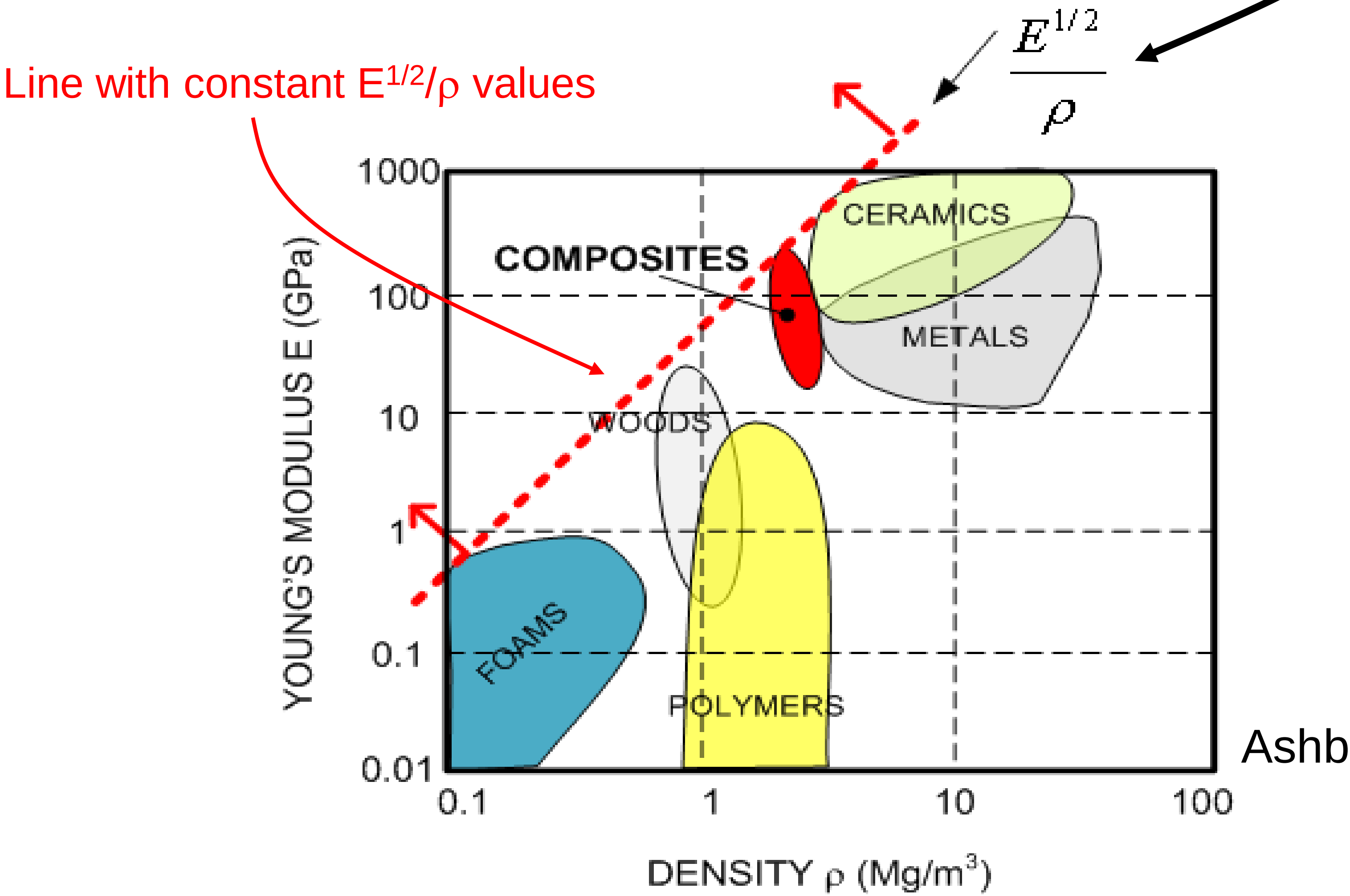
To minimize mass for a given stiffness S we have to maximize $\dfrac{E^{1/2}}{\rho}$

Why composite materials?

Minimize mass for <u>assigned stiffness</u>

$$\frac{E^{1/2}}{\rho}$$

Line with constant $E^{1/2}/\rho$ values



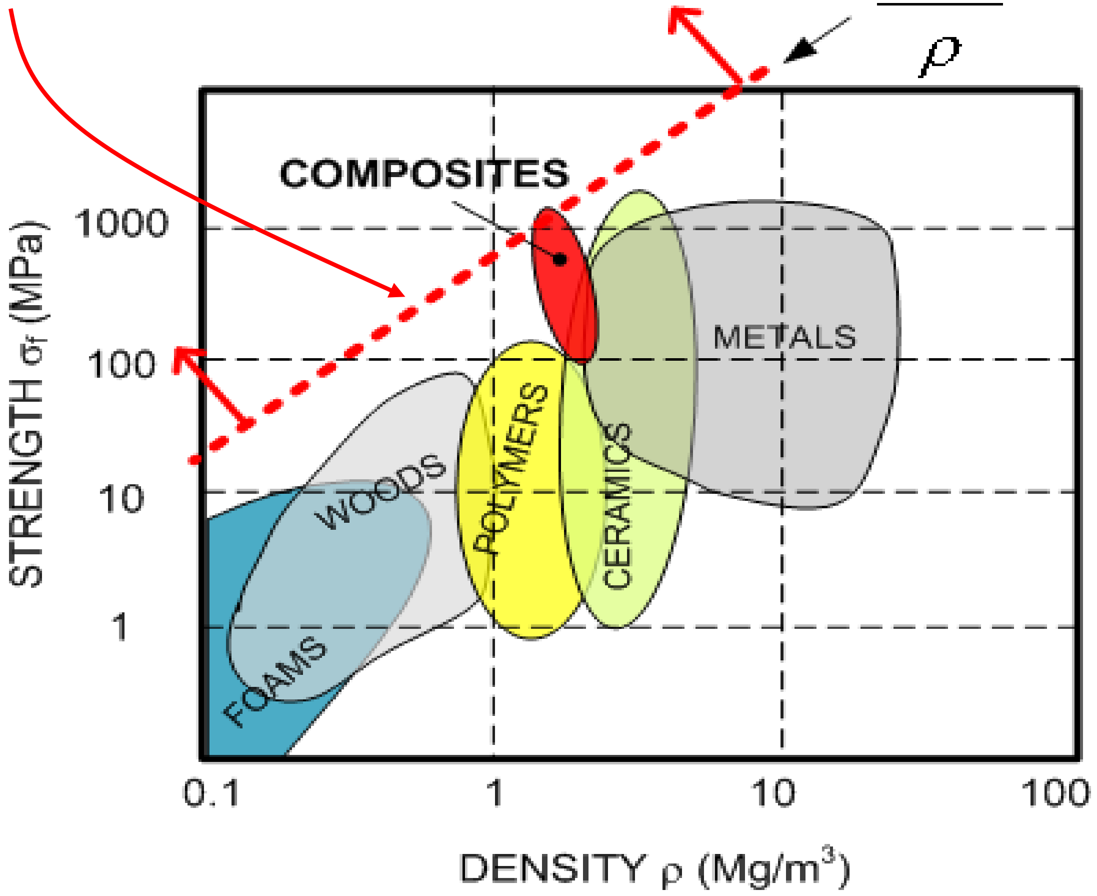
Ashby plot

Why composite materials?

Minimize mass for <u>assigned strength</u>

$$\frac{\sigma_f^{2/3}}{\rho}$$

Line with constant $\sigma_f^{2/3}/\rho$ values

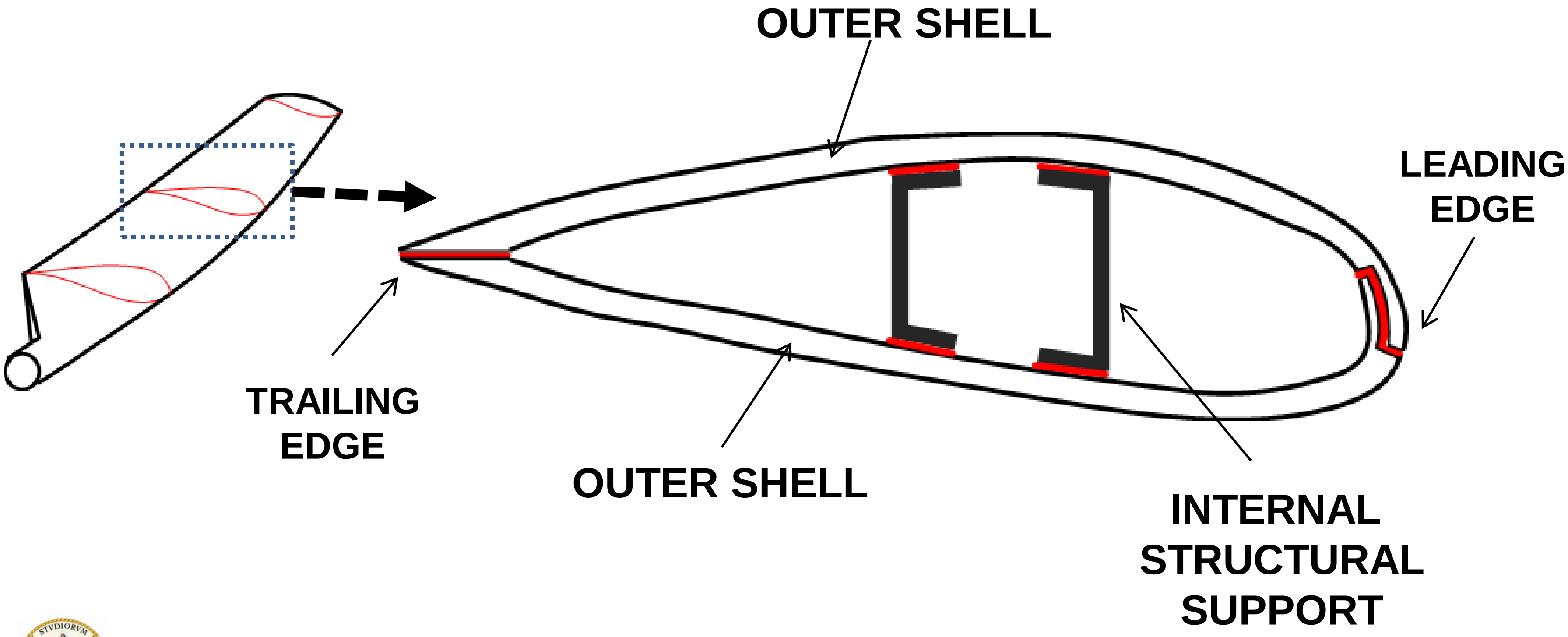


Ashby plot

Cross-section of a blade

The cross-section of a blade consists essentially of :

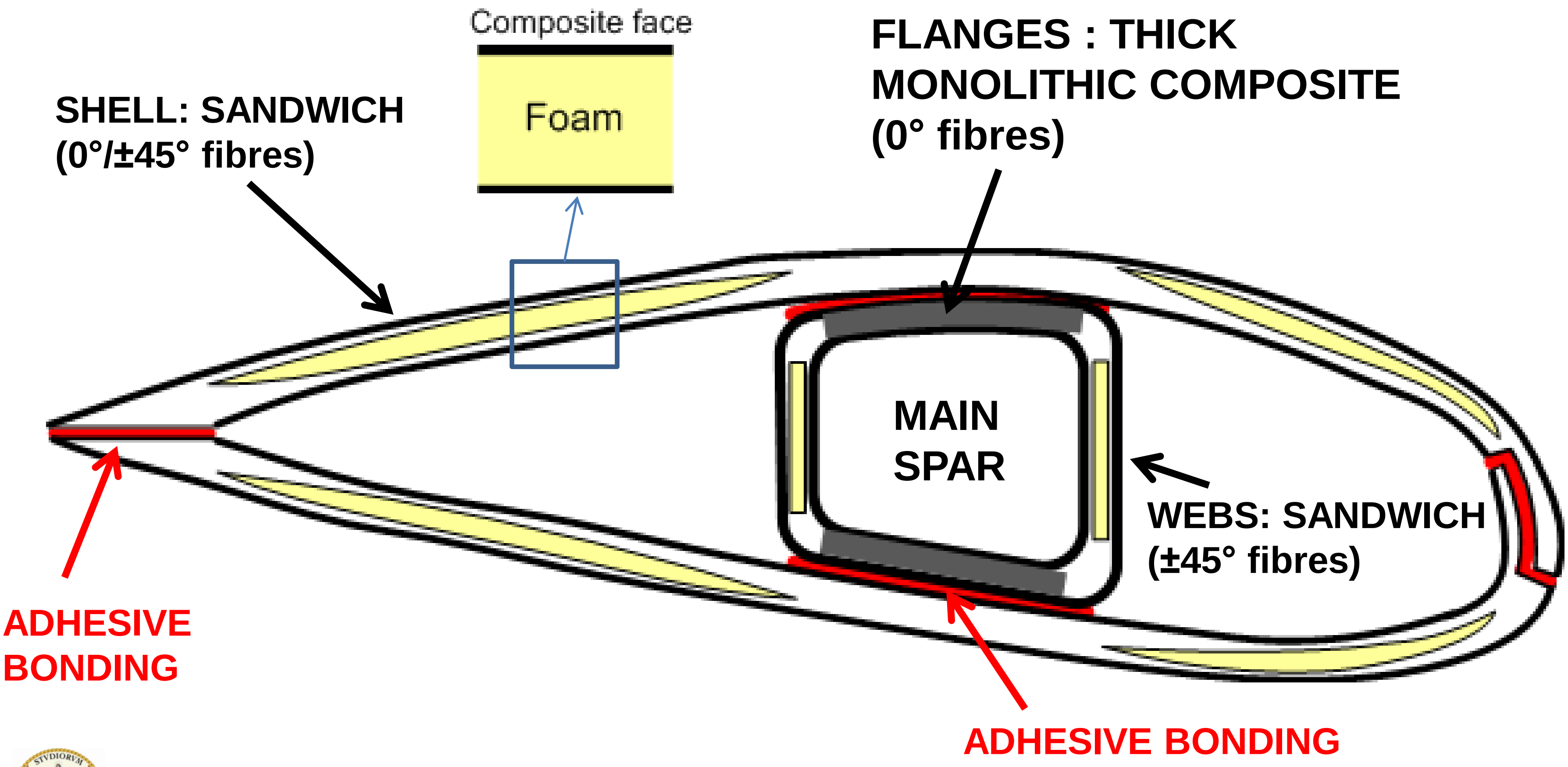
- **Outer shells** (ensure the stability of the aerodynamic shape)
- **Internal structural support** of the outer shells (longitudinal beam or webs)



Cross-section concepts: main spar

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

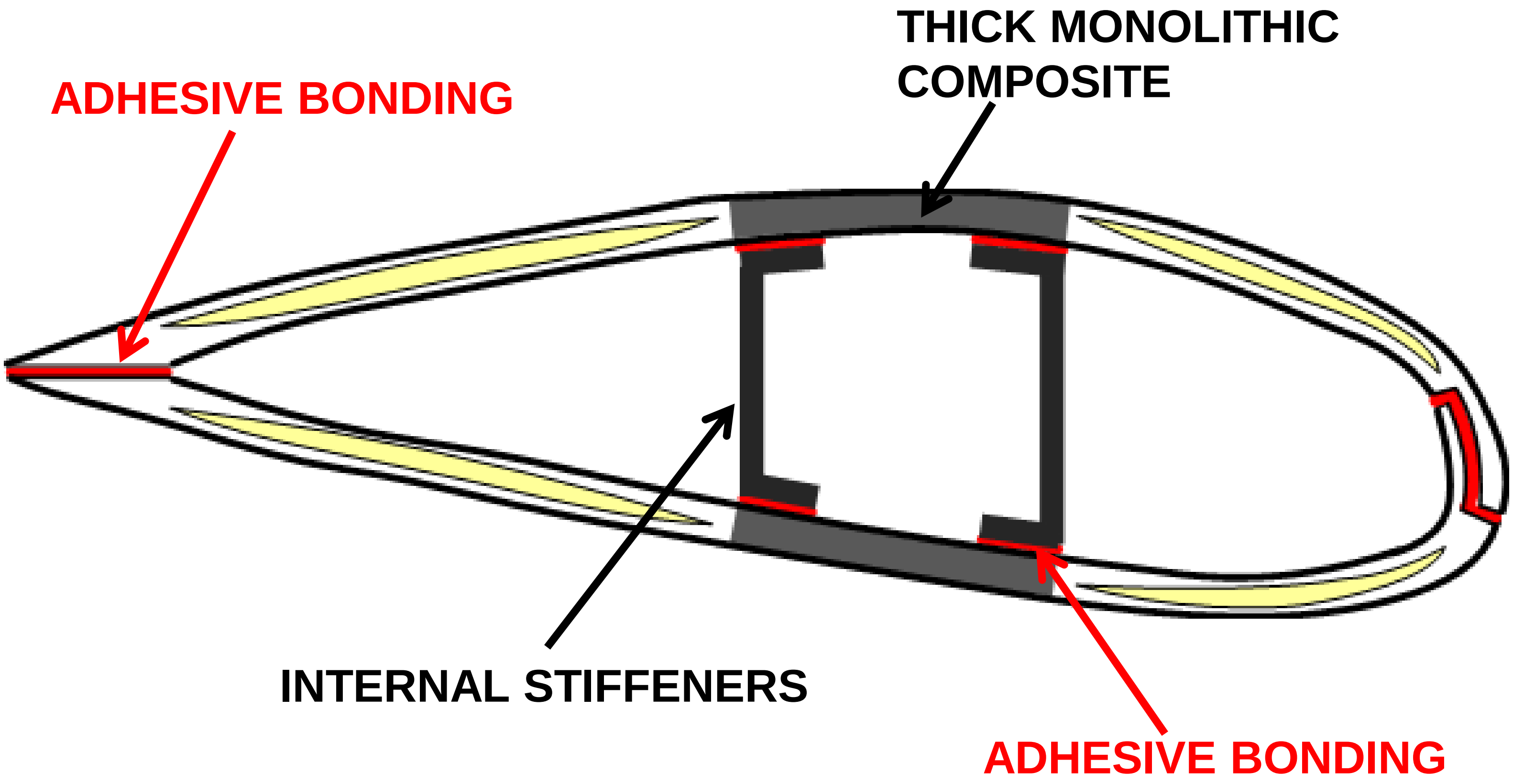
The main spar and the wing shells are manufactured separately and then joined in a separate bonding process.



Cross-section concepts: Internal stiffeners

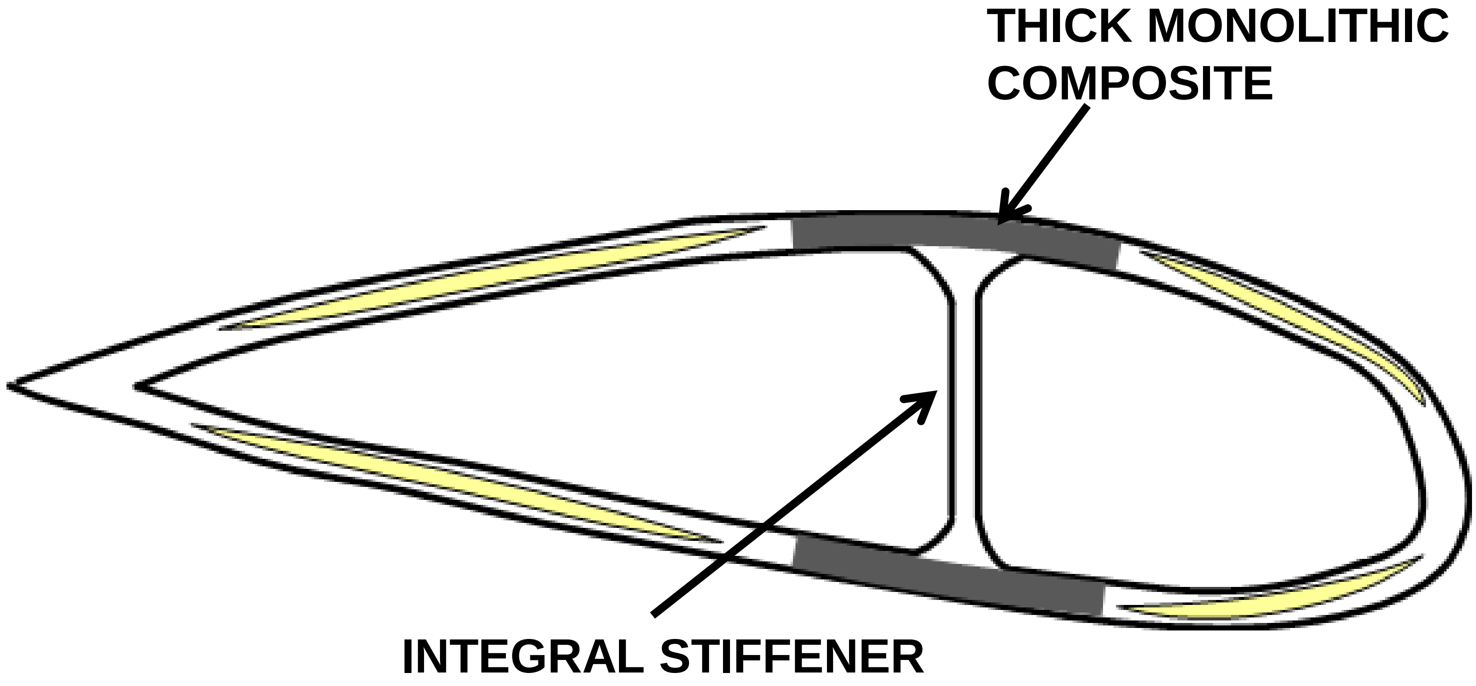
The two aeroshells are bonded to two or more **internal webs** (stiffeners).

The wing shells are manufactured with relatively thick monolithic composite laminates (spar-caps).



Cross-section concepts: Integral stiffeners

The entire blade structure, including internal webs/stiffeners, is manufactured in one single process (**no secondary bonding**).



THICK MONOLITHIC COMPOSITE

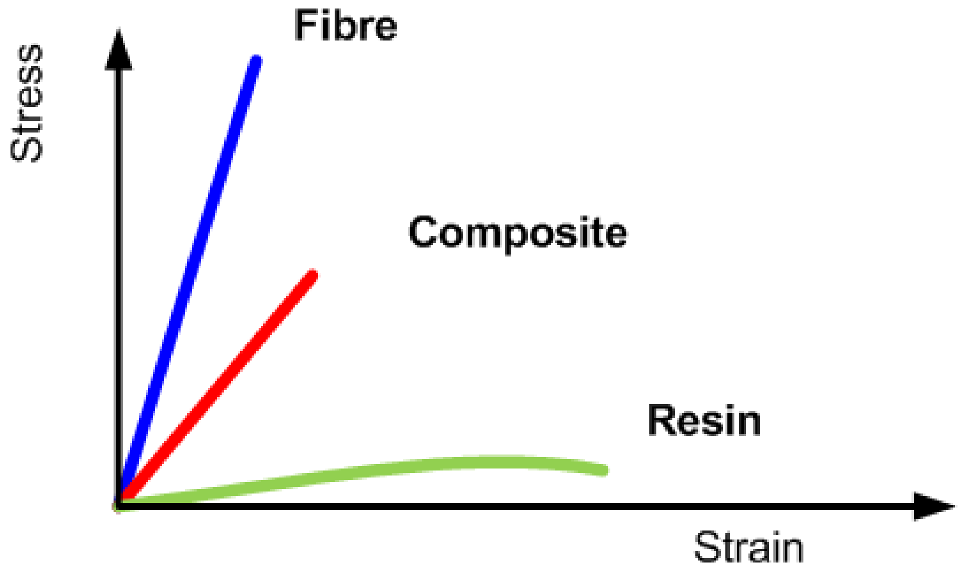
INTEGRAL STIFFENER

Composite materials

A **composite material** consists of two or more materials combined to obtain properties different from those of the individual materials.

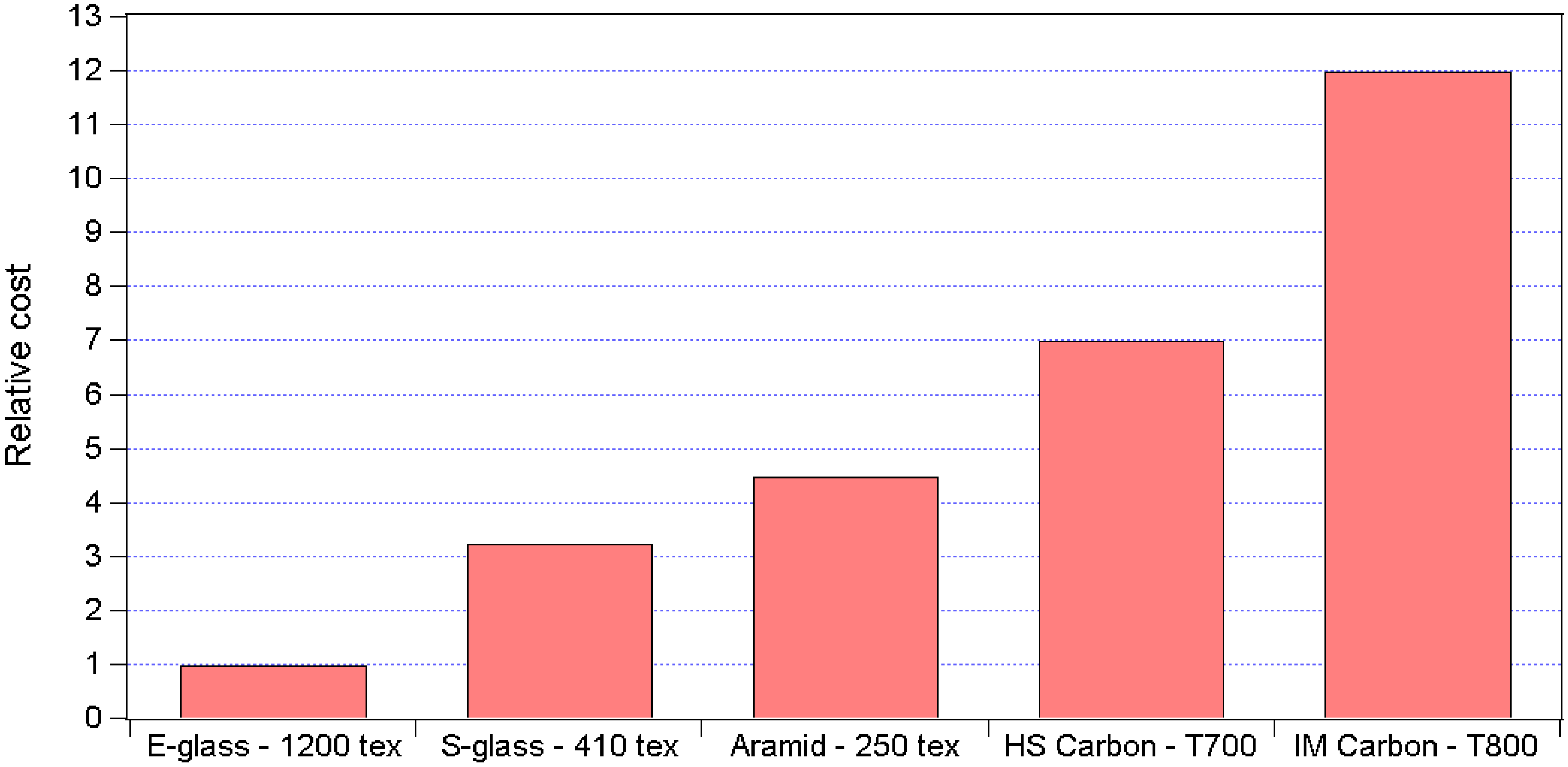
- **Reinforcing fibres** (to add strength and stiffness)
- **Matrix** (holds and protects fibres, and distributes the load)

Polymer Matrix Composite (PMC) materials are typically used in wind turbine blades.



Comparative fibre cost

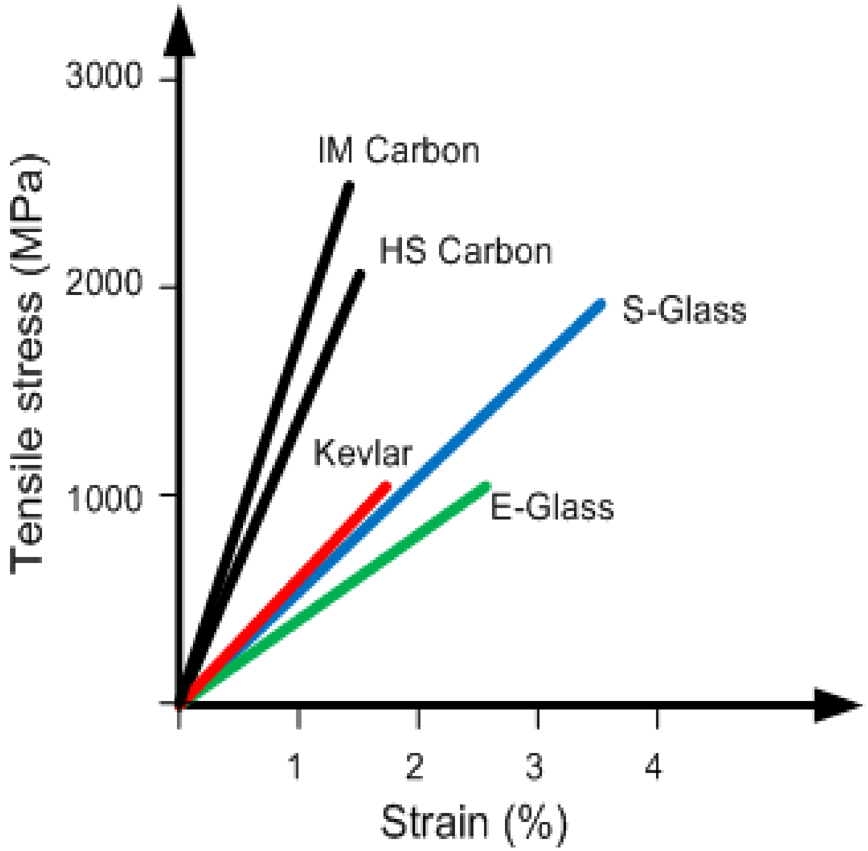
Comparison of fibre cost for unidirectional fabrics (300 g/m^2)

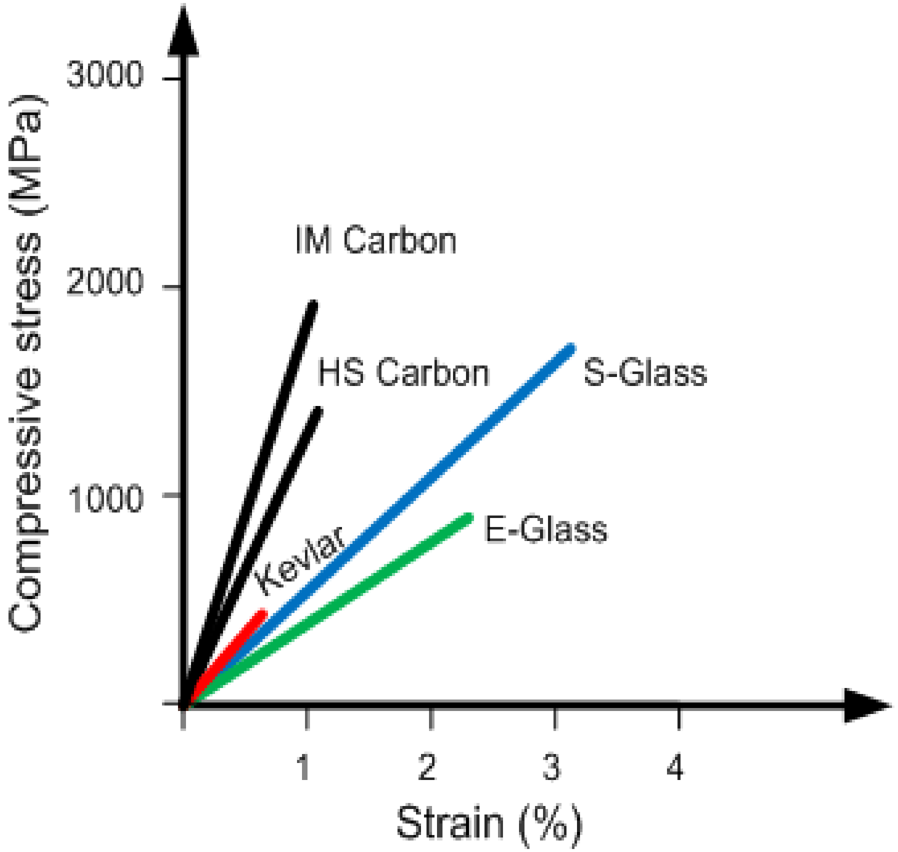


Approximative cost of E- glass = ~ 2.5 Euro/m^2 (~ 3.1 USD/m^2)

[Gurit, 2012]

Tensile and compressive properties of unidirectional composites

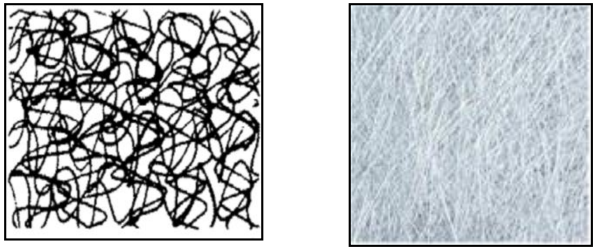




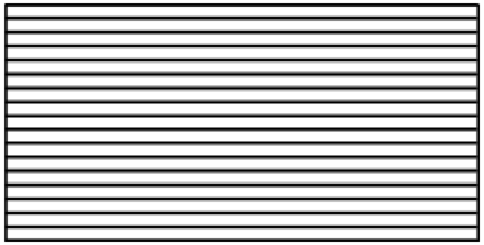
Reinforcement architecture

Common geometries of the fibrous reinforcement include

Continuous or chopped strand mat (CSM)



Unidirectional fibres

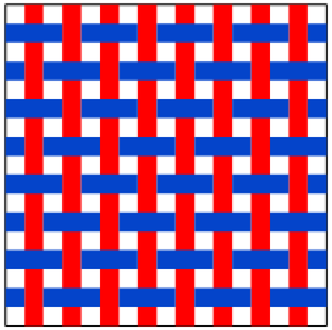


Fabric type reinforcement → **Woven fabrics**

Fabric type reinforcement → **Stitch bonded (Non crimp) fabrics**

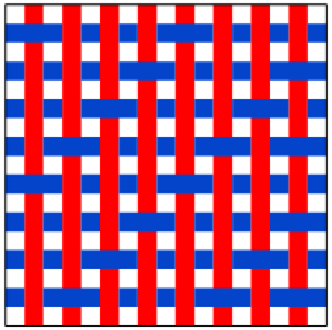
Woven fabrics

Woven fabrics are obtained by interlacing yarns of fibres with different orientations (usually 0° (warp) , 90°(weft), and ±45°)



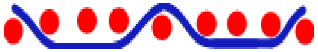
Plain weave

(1 warp yarn
over 1 weft yarn)



Twill weave

(1 warp yarn
under 3 weft yarns)

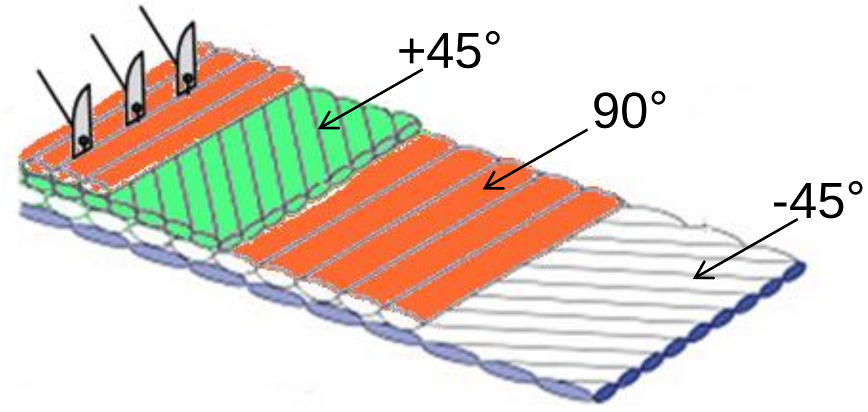


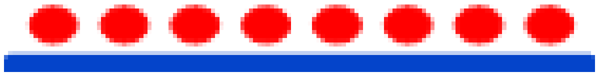
Woven fabrics (vs unidirectional layers)

ADVANTAGES	**DISADVANTAGES**
Higher stability for fibre placement	Lower fibre fraction
Laminates have higher resistance to crack propagation	Lower in-plane properties (crimped fibres and stress concentrations)
	More difficult to infuse with resin

Non Crimp Fabrics (NCF)

Non crimp fabrics (NCFs) are obtained by stitching together unidirectional yarns with different orientations, using non-structural threads.




NCF fabric

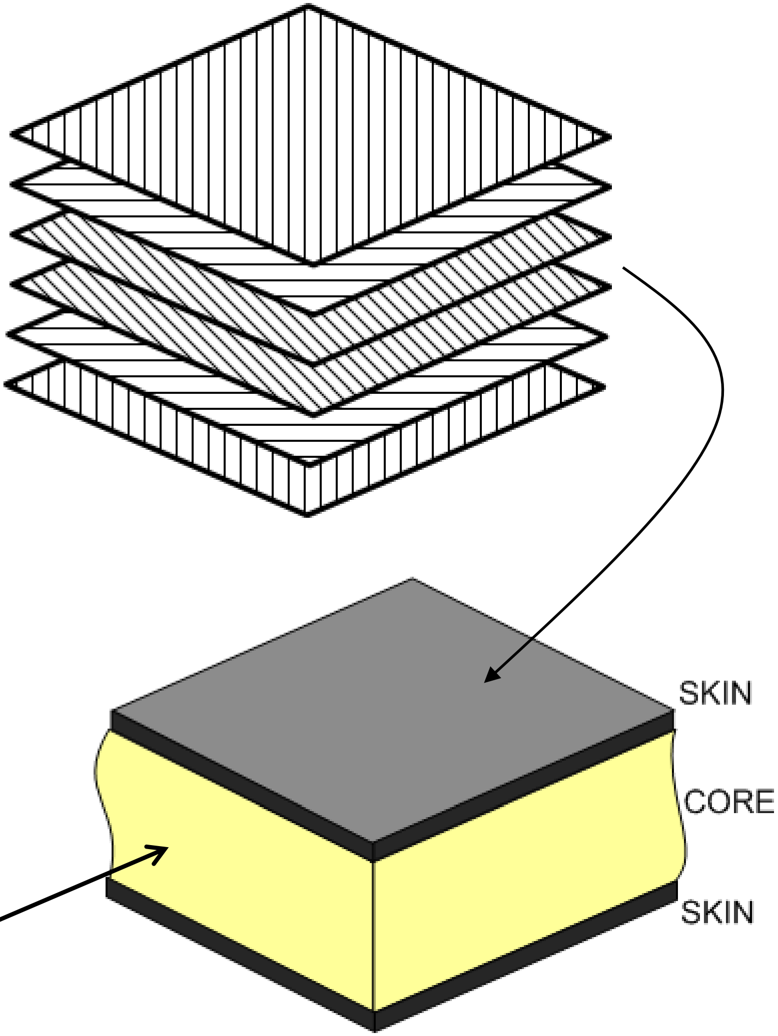

Woven fabric

Non crimp fabrics (vs woven fabrics)

ADVANTAGES	DISADVANTAGES
Higher fibre fraction	Stitching may induce fibre fracture
Higher stiffness/strength (straight fibres)	
No stress concentration due to fibre waviness	
Easier lay-up (fewer layers)	

Basic structural configurations used in blades

Monolithic laminates
consist of different layers of multidirectional fabrics or unidirectional fibres



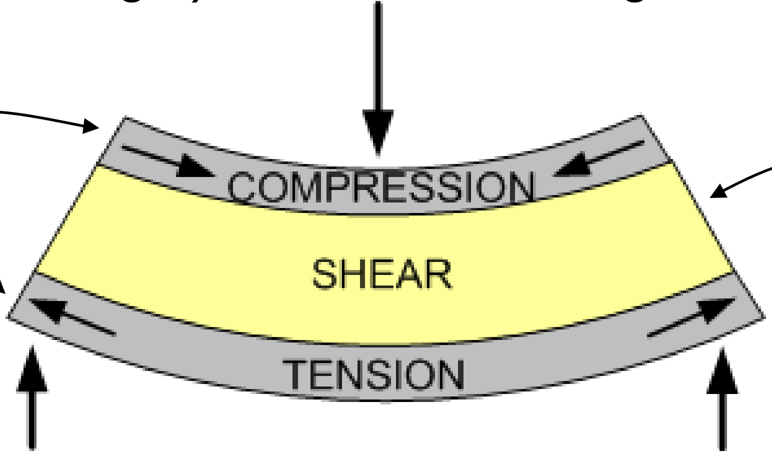
Sandwich composites
consist of of a low-density core between thin faces (skins) of composite material.

Polymeric (PVC, PET, PMI) foams with density in the range 40-200 kg/m^3

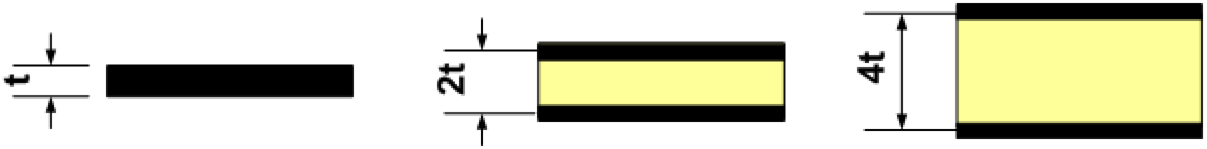
Sandwich composites

The insertion of a core increases the thickness of the structure (and thus flexural stiffness and strength) without increasing its weight.

The skins carry the tensile and the compressive loads



The core carry the shear load

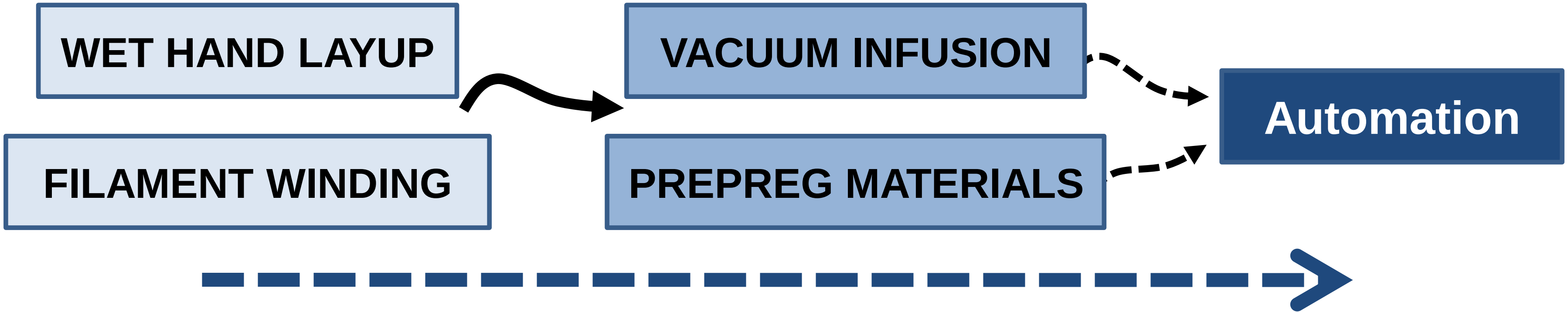


Weight	**1**	⟶	**~1**	⟶	**~1**
Bending stiffness	**1**	⟶	**~12**	⟶	**~48**
Bending strength (M)	**1**	⟶	**~6**	⟶	**~12**

Manufacturing techniques for composite blades

- **Wet hand layup (laminating technique)**
- **Filament winding**
- **Resin infusion**
- **Prepregs**

Potential for automation



WET HAND LAYUP

FILAMENT WINDING

VACUUM INFUSION

PREPREG MATERIALS

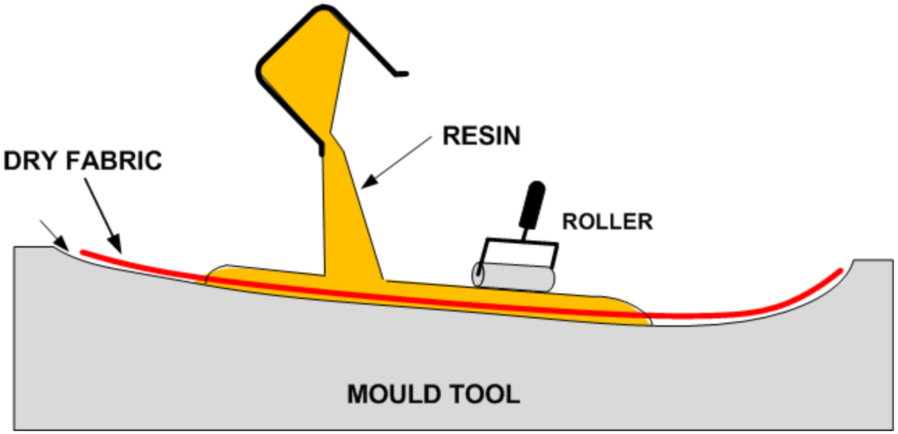
Automation

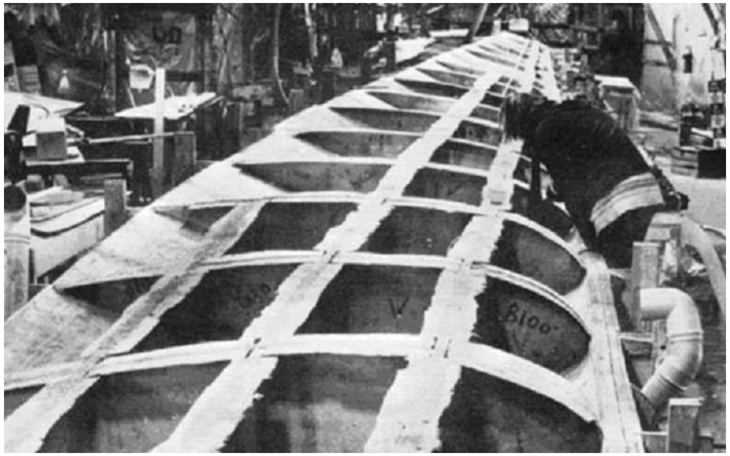
Minimization of cycle times and cost
Reduction of defects
Improved structural performance

Wet hand layup (laminating technique)

Dry fibre material (mats, fabrics or unidirectional tapes) are laid in various layers into the mould of the component.

The layers are then impregnated with resin and cured at room or higher temperature (70° to 100° C for epoxy).





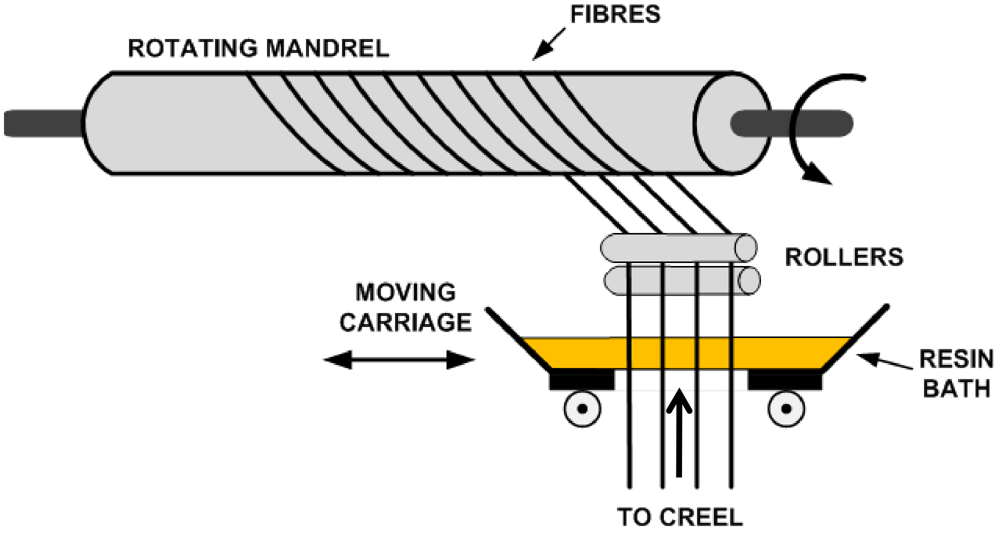
[Brøndsted et al., 2005]

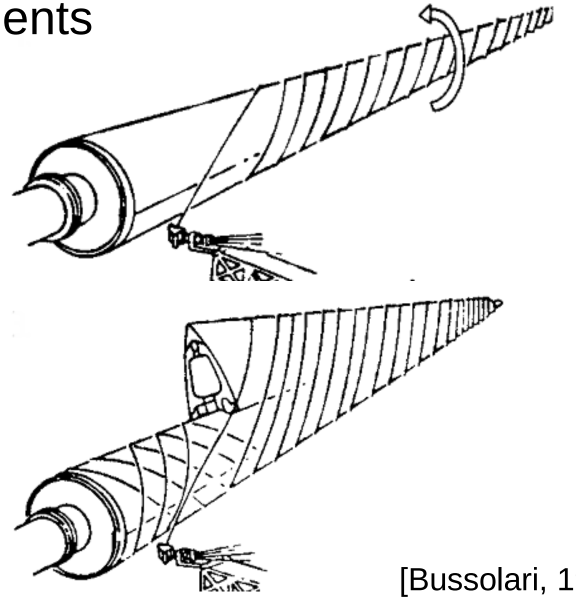
Advantages	Disadvantages
• Production of complex shapes. • Fibres can be oriented along preferred directions	• The process is labor intensive and time-consuming (hand–made) • Large amount of voids and defects • Low fibre fraction

Filament winding

The fibres are passed through a resin bath and are then wound onto a rotating mandrel.

The process is primarily used for cylindrical components but can be adapted for blade manufacturing



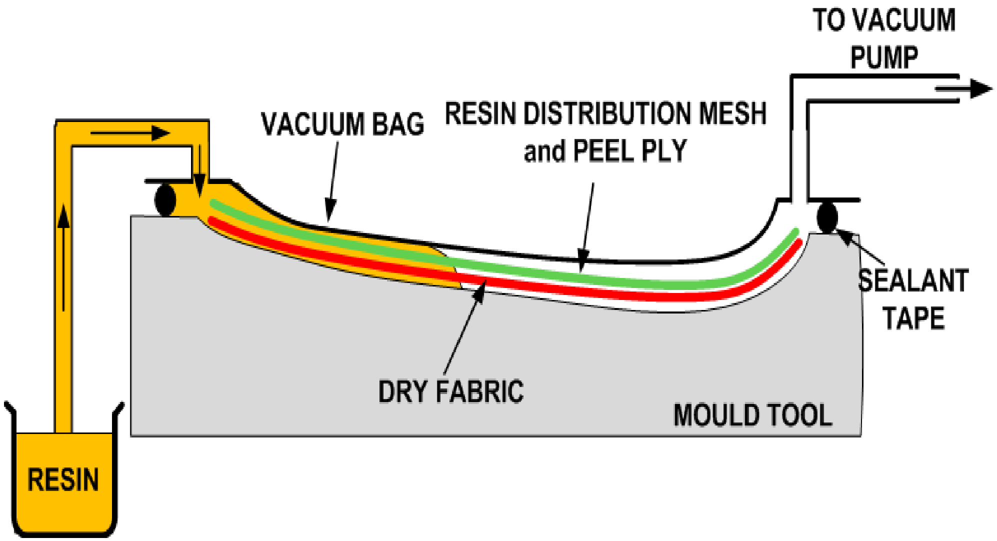


[Bussolari, 1983]

Advantages	Disadvantages
• The process can be carried out in an automatic way.	• Different mandrels must be used to gradually build the airfoil. • Fibres cannot be easily oriented along the axis of the blade (0° direction).

Resin Infusion Techniques

Dry fibres (mats, fabrics or unidirectional tapes) are placed in a mould and encapsulated in a vacuum bag. Liquid resin is then pulled through the reinforcement by vacuum and allowed to cure at room or higher temperature.

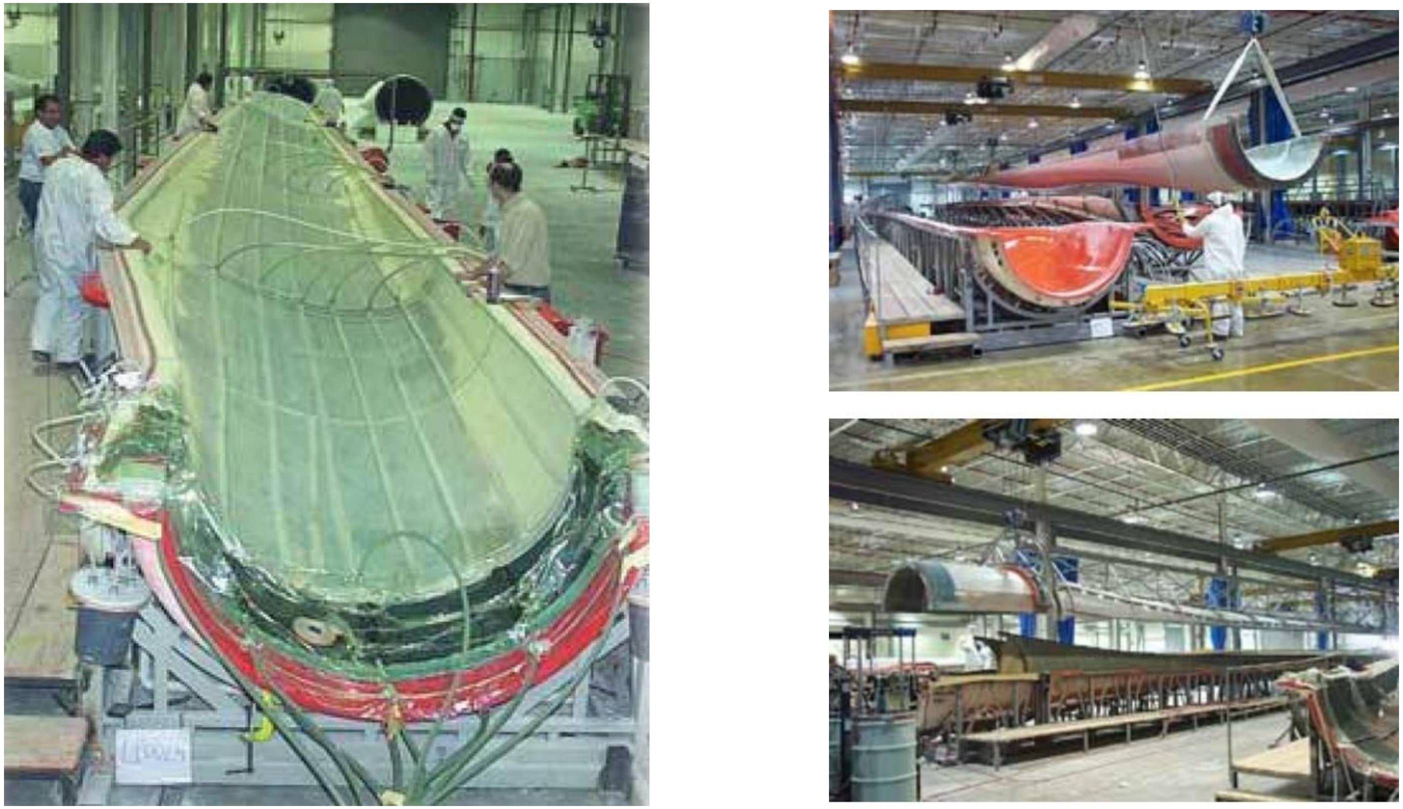


[Grande, 2008]

Advantages	Disadvantages
• Large components can be made in a single step • Clean and safe process • Good final material quality • Potential for automation	• Relatively complex process (especially for large components) • Low viscosity resins should be used (resulting in lower mechanical properties)

Blade Infusion

- The two airfoils and the webs or spar are usually manufactured separately and subsequently bonded to complete the blade.
- In some technologies however the full blade is infused in a single step.



[Hogg, 2010]

Resin Infusion Techniques

Key issues for final quality of resin infusion are:

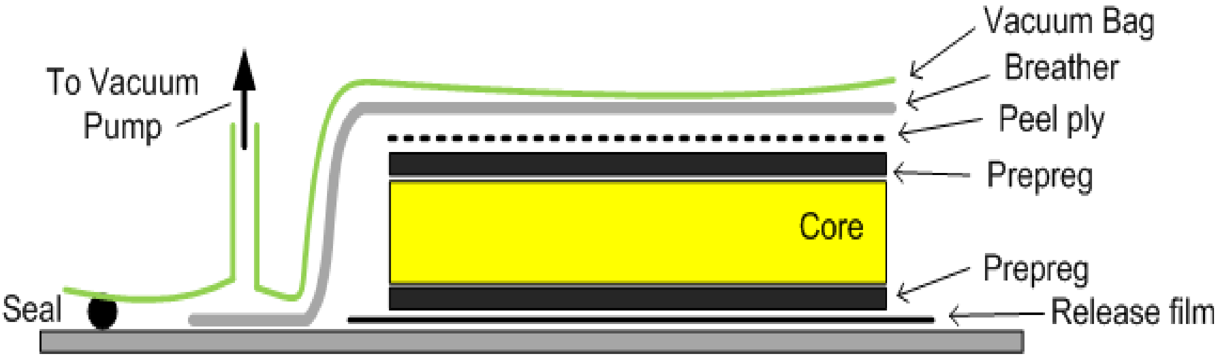
- Improvement of fibre impregnation (to avoid regions with dry fibres)
- Reduction of voids

Possible ways to tackle these issues are
Selection of appropriate fibre coating/sizing to improve wettability
Use of low viscosity resins (at room or moderate temperature) to improve wettability and reduce the process time for large components
Use of fibre fabrics with special architecture (or special resin distribution meshes) to facilitate flow of the resin
Improvement of resin flow (optimal placement of inlet and outlet lines for resin by simulation of the flow and data from sensors)

Prepreg technology

Prepreg tapes consist of fibre fabrics pre-impregnated with a resin that is not fully cured.

The prepregs are laid up onto the mould surface, vacuum bagged and then heated. The pressure required to consolidate the stacked layers of prepregs is achieved by vacuum. Process temperatures range between 70°C and 120°C.



Advantages	Disadvantages
• High fibre ratio and low void content • Consistent material properties • Easy control of fibre alignment • Large components can be made in a single step • Clean and safe process	• High cost for prepreg material • Tooling must whitstand process temperature • It is difficult to correctly cure thick laminates (temperature not uniform through-the-thickness)

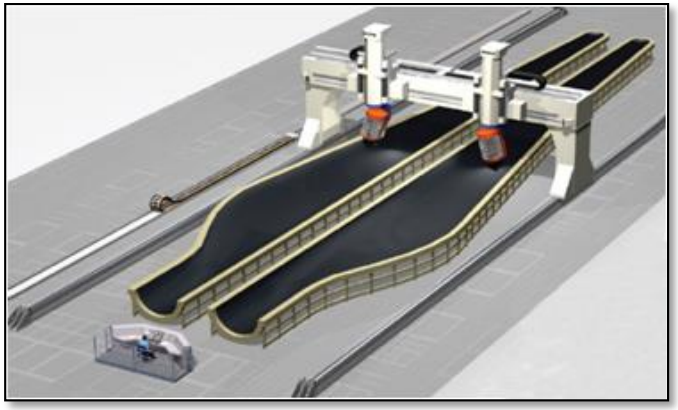
Automation of blade manufacturing

Manufacturing of turbine blades consists of a combination of manual, labour-intensive operations

- Fabrics pattern cutting
- Lay-up
- Vacuum bagging
- Infusion
- Demoulding
- Secondary bonding

To reduce labour and manufacturing time, and improve quality the trend is toward automation

Automated Cutting - Bagging
Automated Tape Layup (ATL)
Automated Bonding



[Black, 2009]