ENGINEERING TRIPOS PART IIA: MODULE 3C1
MANUFACTURING ENGINEERING TRIPOS PART IIA: MODULE 3P1
2012-13

Processing of polymer composites

1. Introduction.

Many natural materials (including wood and bone) are composites. Composite materials typically contain a stiff and strong 'reinforcing phase' dispersed as particles or fibres within a continuous 'matrix' which transmits loads to the reinforcing phase. A composite material often offers attractive mechanical properties combined with low density – with advantages in many applications. Although the matrix of a composite can be metal or ceramic, we shall focus here on polymer matrix composites (PMCs) and review the types of reinforcement, matrix material, processing methods and performance.

2. Reinforcements in PMCs

Many commercial polymers are 'filled' by blending with solid particles – commonly glass or minerals such as calcium carbonate (chalk), talc or clay, or carbon black (especially in rubbers). These can offer benefits in terms of cost reduction, improved processing, density control, optical effects, thermal conductivity, control of thermal expansion, electrical properties, magnetic properties, flame retardancy and improved mechanical properties, such as hardness and tear resistance. These filled polymers are not usually regarded as composites, although they certainly contain two or more components.

PMCs are usually reinforced with fibres, either long (effectively continuous) or short (chopped fibres). Unlike other types of material, the PMC materials themselves are usually formed in the same process that achieves the final shape; that is, the process for making the component also makes the composite material.

Properties of typical fibres and matrices

Material	Density Mg m^{-3}	Young modulus GPa	Strength MPa
Fibre			
Carbon	1.75 – 1.95	250 - 390	2200 - 2700
E-glass	2.56	76	1400 - 2500
Aramid (Kevlar)	1.45	125	2750
Matrix			
Epoxies	1.2 - 1.4	2.1 – 5.5	40 - 85
Polyesters	1.1 – 1.4	1.3 – 4.5	45 - 85

2.1. Reinforcing fibres – typically 8 to 12 μm diameter

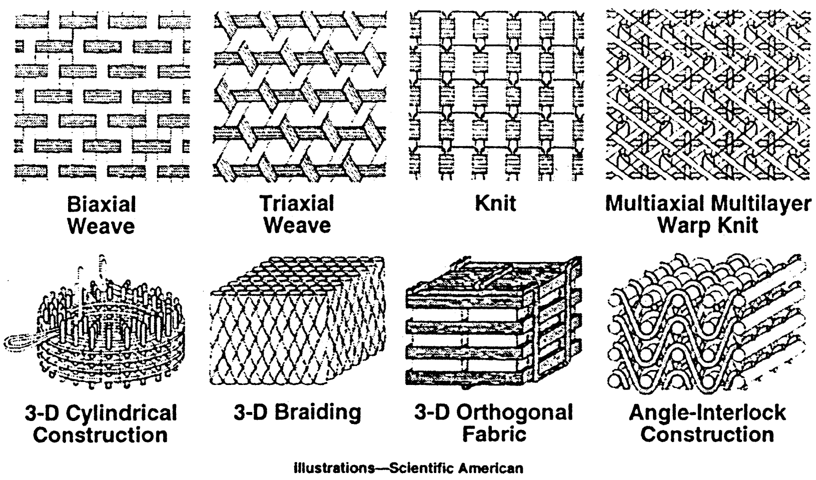
Glass
e.g. E-glass (electrical glass, the commonest general-purpose glass for composites).
Relatively inexpensive. Density ρ 1/3 that of steel; specific modulus (E/ρ) similar; specific strength (σ_f/ρ) 10x greater.
May be used as single or multi-filaments, or woven into cloth
Often chopped to form short fibres (so can use standard polymer forming technologies such as extrusion)

Carbon fibre
Very expensive. High strength; very high specific modulus (E/ρ); high resistance to corrosion, creep and fatigue. Impact resistance less than glass or aramid; poor in compression.

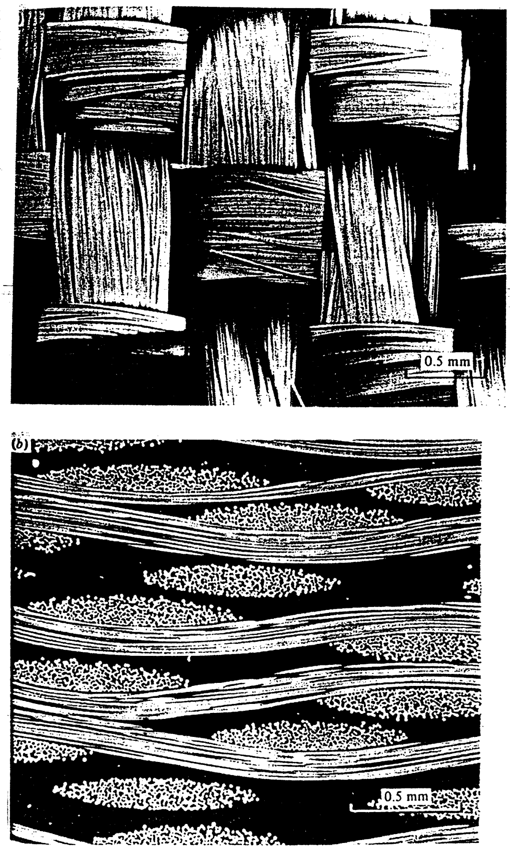
Aramid (a polymer)
e.g. Kevlar (also used in bullet-proof vests)
Very expensive. Yellow fibres containing highly aligned polymer chains. High strength, low density. Extremely tough; excellent impact resistance. Can be UV sensitive.

Other fibres include:
Polyester: low density, good toughness, low modulus, low cost
Polyethylene: highly oriented fibres of ultra high molecular weight polymer (e.g. Dyneema). Very high tensile strength, low density. Difficult to bond to matrix, and expensive.
Ceramic: e.g. silicon carbide monofilament. Very high strength and modulus, very expensive.

For ease of handling, continuous fibres are often formed into rovings (bundles of parallel fibres) which can also be woven to form cloth and other types of textile pre-forms. These are then infiltrated with the matrix polymer in liquid form and cured to form the composite:



Two-dimensional and three-dimensional textile preforms.



(*a*) Scanning electron micrograph of a woven roving before infiltration with resin. (*b*) Photomicrograph of a polished section through a woven roving laminate parallel to one set of fibres.

2.2. Polymer matrix materials

Thermosets

The most common matrix for PMCs; cheaper than thermoplastics. Higher stiffness is advantageous. In order of increasing performance, and cost:

Polyesters

Unsaturated polyesters will cross-link in the presence of accelerators to form a rigid structure. Some restrictions on their use as styrene can be released during curing.
Low cost means generally only used with cheaper reinforcement such as glass.

Vinyl esters

Much better mechanical properties and environmental resistance than polyesters. More expensive.

Epoxy resin

Usually made by mixing two liquid components resin + 'hardener' . Polymer cures by forming chemical cross-links between polymer chains. Good mechanical properties (strength, toughness, high modulus), good environmental resistance. May be more than twice as expensive as polyesters or vinyl esters. Used principally with carbon, glass and aramid fibres.

Thermoplastics
Advantages over thermosets:

Short-fibre composites can be made by conventional thermoplastic processing
Greater potential for high-grade recycling
Tougher matrix
Parts can be joined by welding (using heat and pressure)

Examples:
PEEK (poly-ether-ether ketone); PES (poly-ether-sulphone): High cost, high performance; used with carbon fibre or aramid.
Polypropylene with chopped glass fibre, for low-load automotive applications.
Nylon with chopped glass fibre: electrical, automotive parts

2.3. Combining fibres and matrix

The materials used to make PMC components may be in the form of fibres and matrix separately; more commonly, the fibres may be in the form of a woven fabric, or the fibre and matrix may be combined to form *pre-preg* (i.e. 'pre-impregnated fibres' - see (e) below)

Composite fabrication processes

(Approximately in order of increasing cost)

a. Spray lay-up.
Chopped fibre (glass) and resin + catalyst (i.e. polyester) mixed in a hand-held gun and sprayed directly into the mould or on to the structure. Gives a random 2-D fibre array.

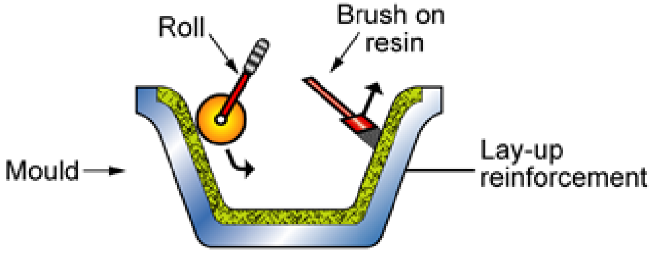
Advantages: Cheap, well-characterised, versatile. "Cheap and cheerful"; also quite foolproof.
Disadvantages: Resin-rich laminates; only materials available are glass fibre and polyester; health hazards from styrene monomer.

Applications: Bathtubs, shower trays, small boats. Good for one-off jobs.

b. Wet lay-up, Hand lay-up.
Resins impregnated by hand (using rollers or brushes) into fibres (generally in the form of woven cloth). Only suitable for low-viscosity resins (may be warmed). Left to cure at room temperature.

Advantages: Reasonably cheap, technique easily learned, versatile. Suitable for a wide range of fibres and resins. Good for one-off jobs.
Disadvantages: Quality of composite very dependent on skill of operator. High fibre volume fractions difficult to achieve. Health hazards from low-viscosity resins and monomers.

Applications: Wind-turbine blades, boats, architectural mouldings.



Roller used to spread resin and remove bubbles

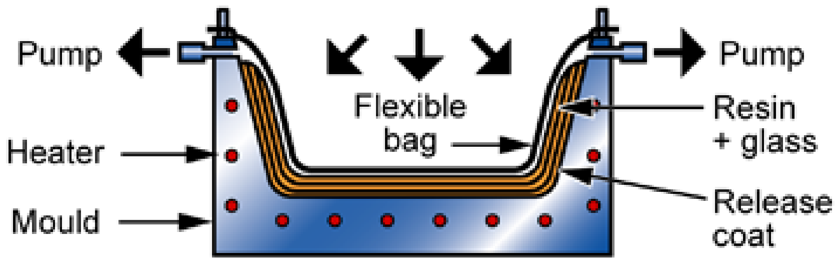
Gelcoat (resin only) on mould surface used to obtain good surface finish

c. Vacuum bagging.
An extension of (b), but quality improved by applying hydrostatic (air) pressure through a flexible membrane before and during curing. Mould may be heated if the process is used to make finished goods; less easily done in the field for on-site repairs.

The material may be supplied in the form of *pre-preg* (cloth plus uncured matrix resin in sheet or tape form)

Advantages: High fibre contents, lower porosity, better process control.
Disadvantages: More costly, greater operator skill needed.

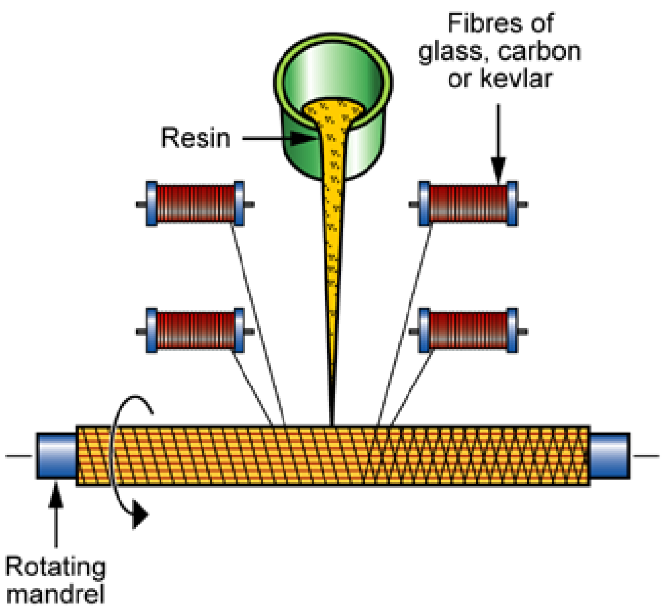
Applications: Large boat hulls, aircraft structures, racing car components. Can also be used for in-situ repairs, e.g. on boat hulls.



d. Filament winding.

Generally used for hollow (circular or oval sectioned) components, though large curved sheets can also be made by carving these up after winding. Fibre tows are passed through a resin bath before being wound onto a mandrel in a variety of orientations.

Advantages: Can be very fast and economical. Resin content carefully controlled. Composite structures can be designed precisely to support the anticipated stresses.
Disadvantages: Limited to convex components. Fibres cannot be laid exactly along the length of a component. Fibre feeding mechanism and mandrel can be expensive. Suitable for low-viscosity resins only.



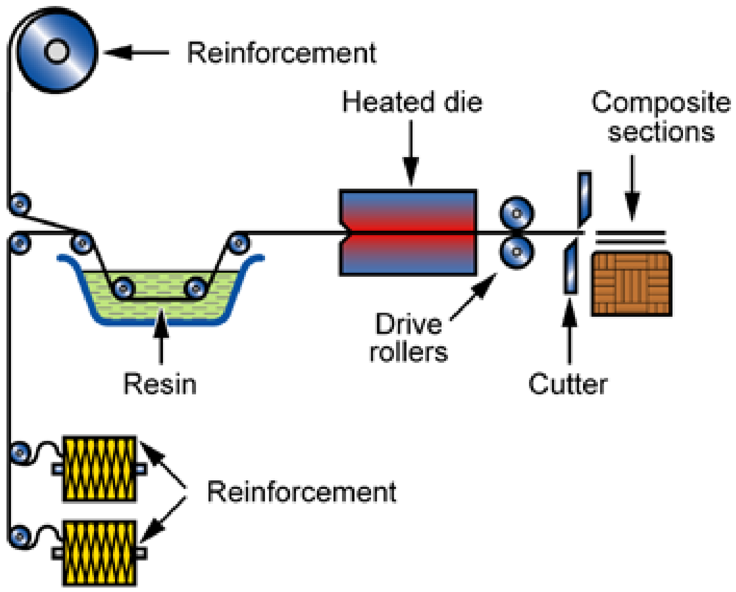
Applications: Chemical storage tanks and pipes, boat masts, gas cylinders, other pressure vessels.

e. Pultrusion.
Can be used either to process fibre bundles in a form which can be used for subsequent lay-up processes (*pre-pregs*, avoiding the need to deal with resin separately at this stage), or can be used to produce composite material in final form.

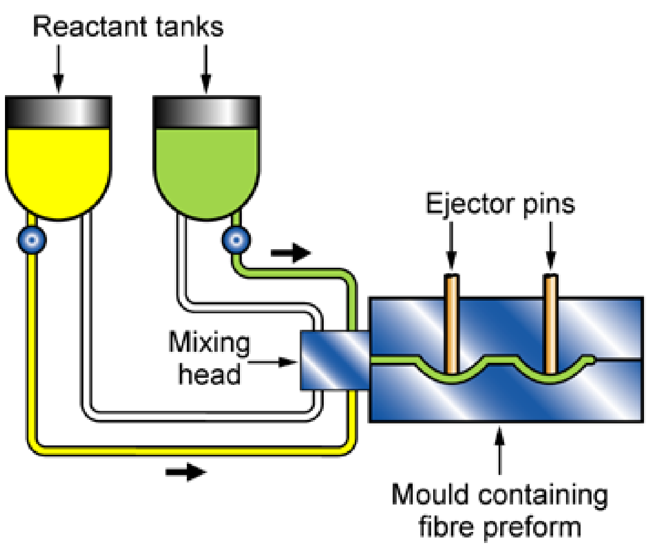
Fibres pulled through a resin bath and then through a die. If the composite is being produced in final form, the die is heated to cure the resin. Pultruded product may be small bundles or tapes of multiple fibres for subsequent processing, sheets (*laminae*, which are used for lay-up processes) or any extruded sections (e.g. rods, I-beams).

Advantages: Fast, excellent fibre alignment (unidirectional: fibres all parallel - NB low lateral strength), good structural control. Good range of compositions.
Disadvantages: Costly (particularly with heated dies), limited to constant-section components.

Applications: Beams and girders, bridges, ladders.



f. Resin transfer moulding (RTM).
Fibre cloth stacked up as a preform in a closed cavity mould, resin injected (if under vacuum, process known as Vacuum Assisted RTM), component cured in mould.



Advantages: High fibre contents, low porosity.

Disadvantages: Costly moulds, very expensive for large parts.

Applications: Small complex aircraft components, train seats.

3. Mechanical properties of PMCs

For good properties, need strong, high-modulus fibres to which load is transferred from the weaker, low-modulus matrix.

Load transfer happens via *shear stress* at the fibre-matrix interface. Bonding at the interface is therefore important.

3.1. Elastic modulus: effect of fibre orientation

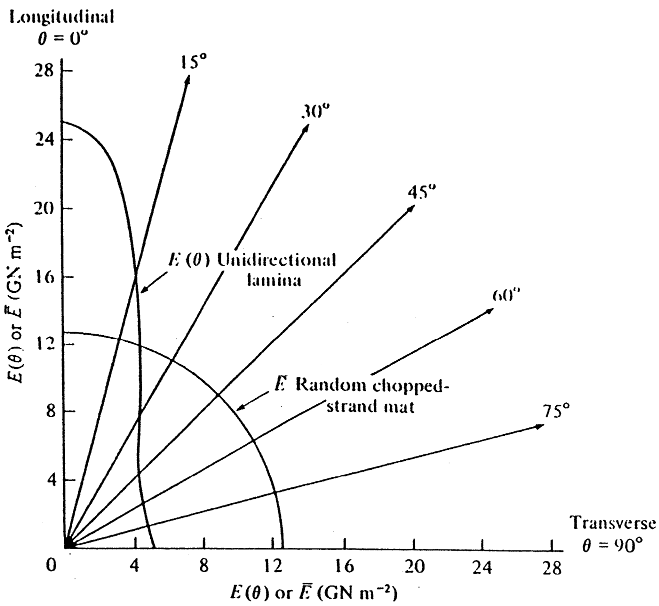
Continuous- or long-fibre composite: highest modulus (and strength) parallel to fibre direction. Equations for modulus E parallel and normal to the fibres, for volume fraction V_f of fibres:

$$E_{parallel} = V_f E_f + (1 - V_f) E_m$$

$$E_{normal} = \left(\frac{V_f}{E_f} + \frac{(1 - V_f)}{E_m} \right)^{-1}$$

Short fibres or particles have intermediate values

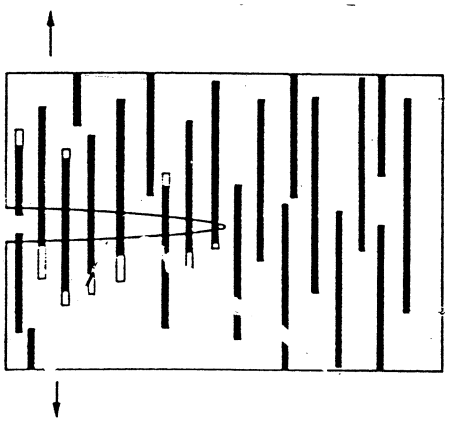
Orientation dependence of Young's modulus of glass fibre–polyester resin ($V_f = 0.30$).



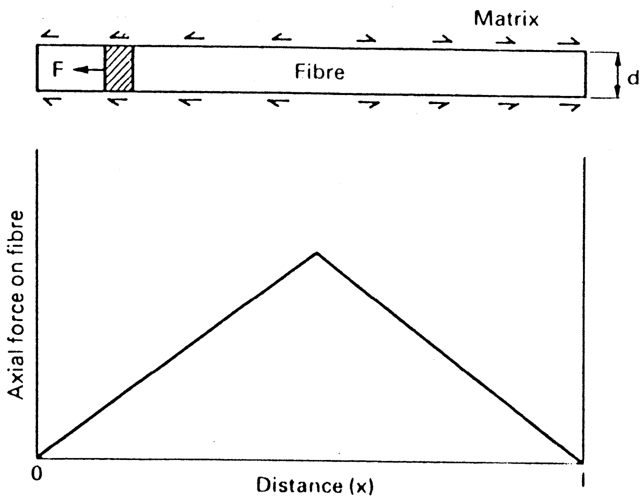
3.2. Strength and toughness

Continuous brittle fibre (e.g. carbon, glass) composites: maximum strength is proportional to the volume fraction of fibres. If load increased enough to exceed fibre fracture stress, then fibres break up into shorter lengths.

Fracture resisted by fibre pullout (from *friction* between fibre and matrix)



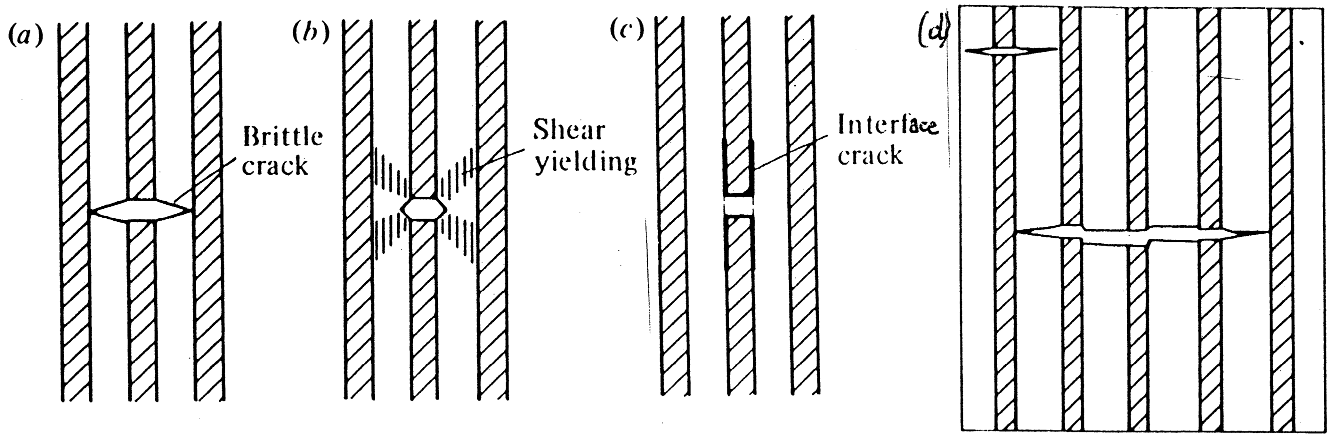
Fibres increase toughness by pulling out of the fracture surface. The work done against friction absorbs energy as the crack opens



Load transfer from the matrix to the fibre causes the tensile stress in the fibre to rise to a peak in the middle. If the peak exceeds the fracture strength of the fibre, it breaks.

3.3. Fracture mechanisms for brittle fibres:

In tension: cracking generally starts with a break in a fibre.
Toughness increased if cracks running normal to fibres can be blunted:



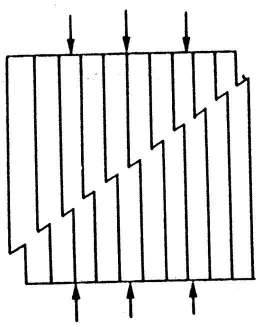
(a) Brittle fibre has cracked. High elastic stresses in matrix at ends of crack.

(b) Ductile matrix: cracks can be blunted by plastic deformation (maybe shear yielding)

(c) If the fibre-matrix interface is weak cracks can be diverted to run along the fibre. (But if it is too weak we lose the load transfer properties. Fibre-matrix bond strength must be carefully controlled)

(d) If fibre-matrix bond is too strong, the crack is not blunted and propagates through both fibre and matrix. Leads to low toughness (i.e. brittleness)

In compression: composites tend to have inferior properties. Fibres buckle and fail by kinking at a much lower stress than in tension. Carbon fibres crush easily, so particularly important that CRFP (carbon fibre reinforced polymer) is used only in tension.



3.4. Delamination

Many composite structures are made from layers of fibre+matrix pre-preg. Layers may be sheets of uniaxial fibres (i.e. all fibres in same direction), or may be woven cloth.
Bonding between the layers is achieved by resin alone, so strength and modulus are low in this direction (often called “secondary properties”).
Stress normal to the layers is liable to cause cracking and *delamination*.

4 Design of composite structures
4.1 Continuous fibre composites

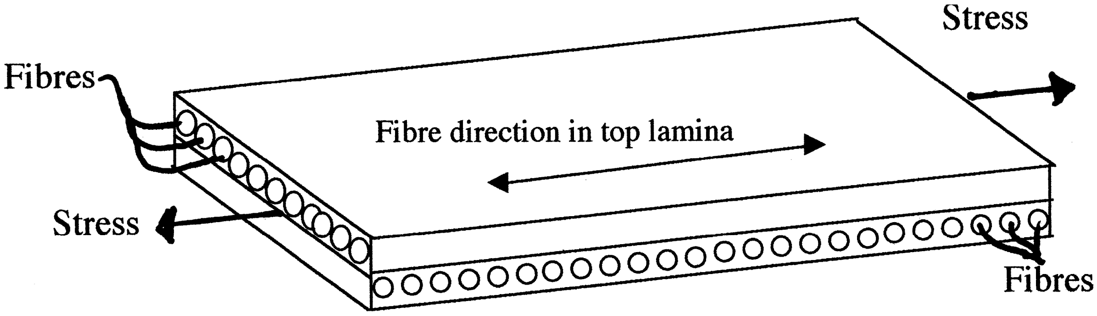
For critical applications (requiring optimum strength and stiffness), continuous fibre composites are used (more expensive than short-fibre). Composite can be designed to accommodate loads by positioning the fibres along directions of maximum stress.

For simple structures, the required fibre distributions can be obtained by laying up sheets (*laminae* or *plies*) of pre-preg. More complex structures may use filament winding or tape laying.

Because the material deforms *anisotropically*, internal stresses are created in a composite as it is loaded.

Example:
0°-90° two-ply laminate under uniaxial stress.

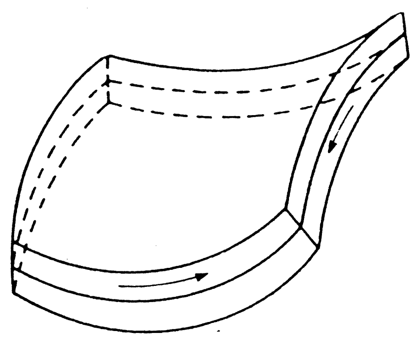
Terminology means: a stack of two layers or laminae each of which contains uniaxial long fibres. The top layer here has fibres at 0˚ to stress axis; the lower layer has fibres at 90˚ to stress axis. These are laid-up and bonded to form a single block of composite.



If we load the composite as shown, then the two laminae experience different strains. The top one is stiff and has low strain. The lower one, loaded normal to the fibres, has high strain. However, the two laminae are bonded together, so they exert stresses on each other. The results are:

- Strain of the composite block is intermediate between the strains for the two laminae loaded in isolation;
- High stress at the **interface** between the laminae (implications for delamination failure; environmental degradation by 'wicking' of liquid such as water between laminae)
- Composite block will suffer **out-of-plane distortion**s, as shown below (mainly because of Poisson ratio effects).

Typical double curvature distortion:
An important principle in composite design is to make sure that these elastic distortions are minimised by making multi-ply composites *symmetric,* giving **balanced layup.** e.g. instead of 0°-90° , use 0°-90°-0° by introducing a third ply at the bottom.



A more complex example of a balanced multilayer layup could be:

$$0, +\theta, -\theta, 90, 90, -\theta, +\theta, 0$$

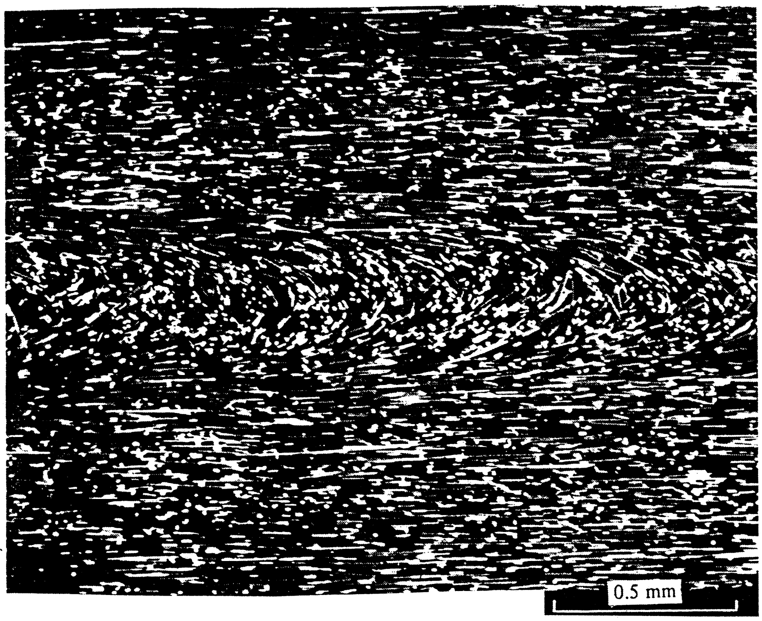
4.2 Extruded short-fibre composites

PMCs containing short fibres in a thermoplastic matrix (e.g. glass-fibre filled nylon or polypropylene) can be extruded using standard polymer technology (screw extrusion), and also injection moulded.

Limitations: like filler particles, fibres increase the melt viscosity. This may place limits on maximum volume fraction of filler.

Extensional flow (see polymers notes) leads to significant alignment of the **fibres** as well as aligning the polymer molecules. The flow pattern of polymers in a channel (polymer notes section 3.2c) gives clues as to how the fibre distribution develops.

Such composites have **anisotropic** modulus and strength. This can provide welcome strengthening in the direction of maximum stress in service, but there is associated weakening in the transverse directions



Longitudinal section through a glass-filled polypropylene extrusion. The glass fibres tend to align parallel to the extrusion direction, especially near the walls where extensional flow is greatest

4.3. Joints in composite structures

The difficulty of producing joints in fibre composites is a serious limitation to their use. In long-fibre composites, the strength normal to the fibres (and normal to the plies) is low, possibly leading to delamination. Standard joints (for joining metals, for example) tend to rely on tensile stresses in this direction for holding the joint together, so cannot be used. Compression joints cannot be used easily either, because composites crush easily.

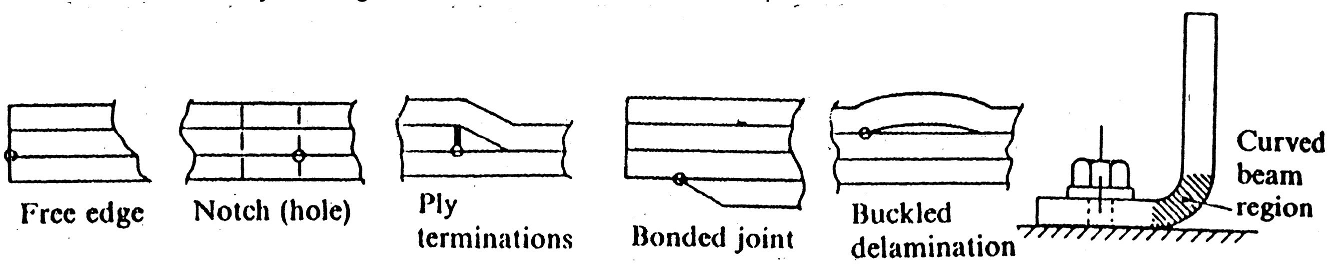
Solutions:

Try to avoid joints altogether (but may still not eliminate out-of-plane stress)

Use compressive joints, but with bulky couplings to minimise stresses

Adopt designs from woodworking technology for strong adhesively bonded joints

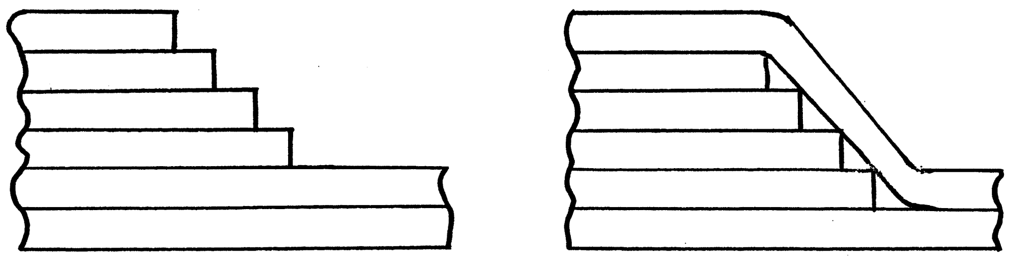
Delamination is likely to originate where there are out-of-plane stresses, such as:



When composite sections need to change (e.g. 6 plies down to 2, as below), there will inevitably be out-of-plane stresses. Their effects can be accommodated by ensuring that stress maxima are **internal.** This has two benefits:

- interior delamination will not provide channels for wicking of fluids in from the exterior
- the continuous surface layers help to maintain integrity

(Note: still need to ensure that layup in both thick and thin sections is balanced)



Further information and sources

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Software:

CES (Process Universe)